AEREA

European Commission

ICAO • OACI • ИКАО

NASA

NOAA

PNEU

UNEP

OMM

WMO

Global Atmospheric Effects of Aviation

Report of the Proceedings of the Symposium

Virginia Beach, Virginia USA

15-19 April 1996

Global Atmospheric Effects of Aviation

Report of the Proceedings of the Symposium

Virginia Beach, Virginia, USA
15 - 19 April 1996

Organisers/Sponsors

Association of European Research Establishments in Aeronautics
European Commission
Intergovernmental Panel on Climate Change
International Civil Aviation Organization
National Aeronautics and Space Administration, USA
National Oceanic and Atmospheric Administration, USA
United Nations Environment Programme
World Meteorological Organization

Host

National Aeronautics and Space Administration, USA

Compiled by the Organising Committee

Daniel Albritton	National Oceanic and Atmospheric Administration
Georgios Amanatidis	European Commission
Giovanni Angeletti	European Commission
John Crayston	International Civil Aviation Organization
David Lister	Defence Evaluation and Research Agency, Association of European Research Establishments in Aeronautics
Mack McFarland	United Nations Environment Programme
John Miller	World Meteorological Organization
Akkihebbal Ravishankara	National Oceanic and Atmospheric Administration
Nelson Sabogal	United Nations Environment Programme
Narasimhan Sundararaman	Intergovernmental Panel on Climate Change
Howard Wesoky	National Aeronautics and Space Administration

Table of Contents

Objective of the Symposium

The objective of the organisers of the Symposium on the Global Atmospheric Effects of Aviation was to bring scientific, technology, and policy leaders together to review the status of all relevant atmospheric research, for discussion of potential mitigation measures, and to consider what policy-relevant information may be available to decision makers in the next few years.

Specially-focused studies to understand and reduce aviation's environmental impact are currently supported and carried out by governments and other organisations throughout the world. These include the European Commission, National Aeronautics and Space Administration (USA), and National Oceanic and Atmospheric Administration (USA) and members of the Association of European Research Establishments in Aeronautics.

Scientific assessments in support of the Montreal Protocol, which recently have included consideration of aviation, are conducted by the Protocol's Ozone Science Panel. The Intergovernmental Panel on Climate Change provides scientific-technical advice to the Framework Convention on Climate Change and its assessments independently to all governments for their use in national policy making. Both of these panels operate under the auspices of the United Nations Environment Programme and the World Meteorological Organization. Standards to control emissions from aircraft are established by the International Civil Aviation Organization (ICAO)- itself a United Nations specialised agency, based upon recommendations from its Committee on Aviation Environmental Protection (CAEP).

Actions have already been taken which promise a closer relationship between ICAO and UN scientific organisations in the coming years, and future international environmental assessments are likely to devote more attention to aviation. The organisers therefore decided that it was timely to begin consideration of those assessments, the related research programmes, and the expected outcomes for decision makers. In view of their common interest in minimising aviation's detrimental effects on the atmosphere, these major organisations joined to co-ordinate the Symposium.

I. Introduction

The interaction of aircraft with the global atmosphere is a unique one, as the following aspects indicate:

- *Aircraft emissions occur predominately in the upper troposphere and lower stratosphere.* This is in contrast to surface-level pollution sources, which are subject to effective removal processes (e.g., rainout). As a result, although there are local and regional impacts close to the surface arising from emissions around airports, the primary concern here is with global impacts occurring at the higher altitudes.

- *The relevant chemical and dynamical processes at aviation cruise altitudes have proven challenging to understand.* The processes involved are different from those near the surface. The chemical and meteorological time scales can vary widely. They also can be comparable to each other, yielding a scientific problem that requires a simultaneous understanding of both. The species involved in the emissions occur in a wide range of densities, ranging from relatively dense plumes to trace global background levels.

- *The species emitted by aircraft are involved in various ways with multiple environmental issues*, including stratospheric ozone-layer depletion, radiative forcing of climate change, and changes in tropospheric chemical composition. For example, carbon dioxide is a direct component of global warming, while emitted particles can influence ozone depletion and cloud formation, both of which in turn influence the radiation balance.

The knowledge of the impacts of aircraft on the atmosphere is rapidly expanding. Many of the identified impacts are beginning to be quantified, such as the production of tropospheric ozone as a result of nitrogen oxide emissions. Others, however, are at the qualitative stage of understanding, such as the role of particles. Consequently, the full environmental impact of aviation in all of its aspects is very difficult to characterise at present. Since continued growth in aviation is forecast, all of this points to the value of a broad assessment of the current understanding of the phenomena involved.

Similarly, the technical and economic options associated with amelioration of potential impacts have special requirements or constraints:

- *Safety is paramount.* Continued improvement in safety is the dominant consideration for the industry in assessing any potential engineering and operational changes.

- *The options for alternative fuels are quite limited.* In contrast to surface transportation, there presently are no practical alternatives that have the energy

content per unit weight of aviation kerosene.

- *The complexity with which aircraft emissions interact with the environment is a challenge to potential policy decisions associated with aircraft and engine design and operation.* Mandated measures to reduce the emissions of one species may lead to increased emissions of others; therefore, trade-offs among emissions must be examined with regard to the *net effect* of a policy decision: is it environmentally positive or negative? Impacts can vary with altitude, position, and timing of emissions, and again there are trade-offs to be considered.

As a result, appropriate policy considerations regarding the environmental role and potential future decisions among options require an *integrated analysis* of atmospheric processes, technical options, and costs/benefits, at least to first order.

The need for such an assessment is clearly there. Decisions regarding a possibly expanded fleet of supersonic aircraft may lie within the next few years. For subsonic aircraft, their emissions burden may double in the next two decades or so. Questions regarding their future (and current) impact on climate are being raised in policy circles now. The consequences of such decisions (or non-decisions) regarding aviation will persist for decades, since the operational lifetime of engines and airframes are on that order, as well as being comparable to typical times for economic returns on investments.

This report is the summary of a Symposium involving atmospheric scientists, aviation technologists and economists, and national and international policymakers whose aim was to move a step closer toward making such an integrated assessment of the aviation issue available. Following the introduction, the capsules of discussions of various facets of the issue comprise the main body of the report, concluding with a summary of discussions regarding the way forward. The report is **not an assessment** of the issues, but provides a summary of the presentations of a number of invited speakers and the ensuing discussions within the Symposium.

Lastly, appended material gives additional information regarding the symposium. Appendices A and B list the symposium's agenda and participants. Appendix C is a summary of the policy questions that provided the context, and Appendix D is an overview of the major research programs that are underway to improve the scientific aspects of the issue. Appendix E is a glossary of terms common to aviation related atmospheric research. Appendix F is a bibliography to assist those readers who wish to pursue additional information about the subject of the symposium.

A. Atmospheric Science

Figure I-A-1 illustrates the manifold ways in which aircraft emissions can interact with the atmosphere. Further, it depicts the major environmental issues to which these emissions are related.

Several decision-relevant features of the global atmospheric impacts are noteworthy:

- *Two* global-change phenomena and major environmental issues are directly involved: ozone-layer change and climate change.

- Many of the impacts depicted are *not the "classical" mainstream research/policy interactions* of these two issues, which have been (i) ozone layer depletion via globally mixed halocarbon emissions and (ii) greenhouse warming via globally mixed carbon dioxide emissions from fossil fuels.

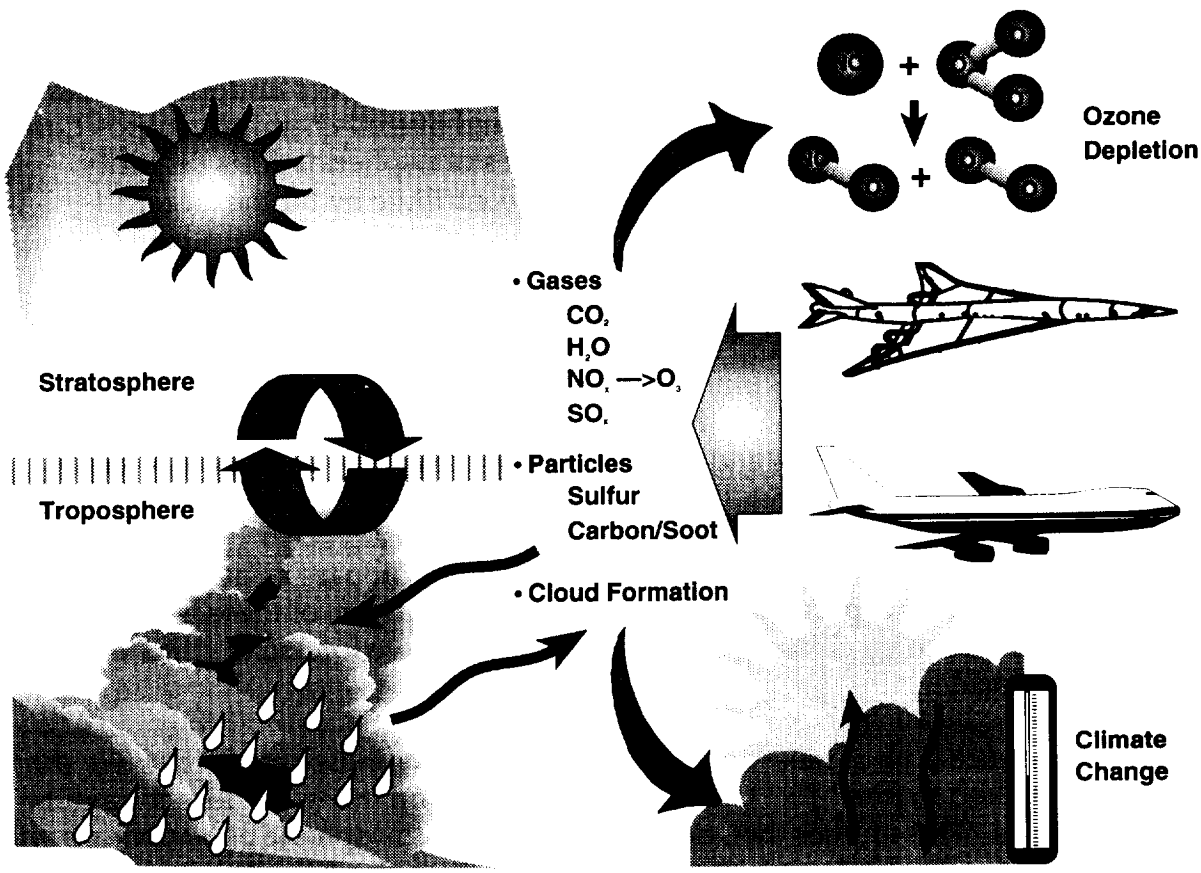

Figure I-A-1. Aircraft Emissions and the Global Environment

- The emissions are in the *least well-understood* regions of the atmosphere - the lower stratosphere and the upper troposphere, which are also dynamically coupled in ways not well understood.

- The principal emissions differ substantially: (i) gaseous - CO_2 (carbon dioxide), H_2O (water vapour), NO_x (nitrogen oxides), CO (carbon monoxide), HCs (hydrocarbons), and SO_x (sulphur oxides) and (ii) particles - sulphur based and carbon based.

- The impacts can be *direct* ($CO_2 \rightarrow$ radiative forcing $\rightarrow$ climate) and *indirect* [(i) particles $\rightarrow$ cloud formation $\rightarrow$ radiative forcing$\rightarrow$ climate and (ii) $NO_x \rightarrow$ ozone change $\rightarrow$ radiative forcing $\rightarrow$ climate]. It is the indirect responses of the atmosphere that are the most difficult to evaluate.

- Substantial *natural sources* of some of these emissions and reaction products exist, e.g., downwelling of ozone from the stratosphere into the troposphere and production of NO_x by lightning, and the associated uncertainties are quite large.

- The *depth of scientific understanding varies considerably* regarding the various aspects of this issue, e.g., the potential impact of supersonic aircraft on ozone-layer change (which is almost wholly stratospheric) is better understood than the potential subsonic aircraft impact on climate and overall chemical composition (which is mostly tropospheric, but somewhat stratospheric). This disparity occurs despite the fact that subsonic aircraft contribute by far the larger proportion of aircraft emissions.

- Many of the impacts are very *altitude-sensitive*: For example, NO_x can deplete ozone at higher altitudes and create it at lower altitudes.

- Aircraft emissions are (and will be) occurring in a <u>changing atmosphere</u>, which will influence the absolute and relative magnitudes of the impacts of aircraft emissions.

- For both issues, decision makers will likely seek to compare aviation impacts to the more familiar aspects (to scientists and policy makers) of these issues: ozone depletion caused by chlorofluorocarbons and radiative forcing of climate by carbon dioxide.

- The residence time of most aircraft emissions in the atmosphere is *relatively short* , say compared to fossil-fuel CO_2, whose removal is on many-decades to century time scales. This implies that, except for CO_2, the atmospheric perturbations will rise or decay quickly in response to changes in these short-lived emissions; therefore, for these short-lived emissions, it is the level of the *ongoing* annual emissions that is the policy-relevant point, not the longevity of any one year's emissions (as it is with the long-lived CFCs with regard to the ozone depletion).

B. Technological and Economic Aspects

As a clear understanding of aviation's contribution to global atmospheric problems emerges, the search for appropriate solutions to control aircraft emissions is likely to encompass new technology, new operational procedures, and the wider use of economic instruments.

- In the absence of practical alternatives to aviation jet fuel - at least for the foreseeable future - *new technological advances* are likely to focus on improved engine and airframe design.

- Emissions of CO_2 and water vapour from aircraft engines can only be reduced by reducing fuel consumption. Driven by market forces (fuel costs represent about 15% of airlines' costs), aircraft and engine designers already place a high priority on *fuel efficiency*. Further improvements are anticipated, but they are likely to be outpaced by aviation's rapid growth rates. As a result, on a business-as-usual basis, aviation fuel consumption - and hence CO_2 and water vapour emissions - are expected to continue to grow.

- While emissions could be reduced for a given aircraft and flight route if fuel consumption were reduced (and other factors remained equal), there is also scope for reducing emissions through changes in *engine design*.

- In the case of SO_2 and sulphur particles, there may be scope for emission reductions through lowering the *sulphur content* of aviation fuel.

- There may be some *trade-offs* between these various emission reductions. For example, the improvements in fuel efficiency that have been achieved over the years have tended to come from raising the temperature and pressure at which fuel is burnt. Unfortunately, this also encourages the production of NO_x. Engine manufacturers' choices of engine design and combustor technology will determine relative performance with respect to CO_2/water vapour and NO_x.

- The lifetime of an aircraft can be 25 years or longer and therefore *fleet renewal* takes place fairly slowly. Aircraft entering the fleet today are replacing aircraft that entered service in the early 1970s and that may have been designed some years earlier.

- While the emphasis is likely to be on what technology can do, *operational* measures could offer some benefits. These include measures to reduce the amount of fuel consumed, such as reductions of cruise speed and improving load factors, and measures aimed at reducing the impact of emissions, such as optimising cruise altitudes and restricting flights through atmospheric regions that are particularly sensitive.

- With increasing use being made of economic instruments by governments, the question arises as to whether there are potential roles for *environmental charges and taxes* or *cap-and-trade approaches* to control aircraft engine emissions.

- *The stakes are large:* According to International Air Transport Association (IATA) estimates, the annual turnover of its member airlines was $230 billion (U.S.) in 1994. A study by the International Civil Aviation Organization (ICAO) in 1992

estimated that, on a business-as-usual basis, some $800 billion (U.S.) of investment funds will be required over the next 20 years for air carrier fleets and about $250 - 350 billion (U.S.) for airport and en route facilities.

C. Interface of the Science/Technology and Policy

Current and past environmental decision making by the spectrum of policy communities (local to international) has included consideration (at varying levels of sophistication) of the costs and benefits of potential actions (or inactions). The scientific, technical, and economic communities have helped assemble the necessary information for such decisions and, in advanced cases, to lay this information out in the form of options.

The vehicle for providing this information has been the international state-of-understanding assessments. As depicted in Figure I-C-1, they are the interface between

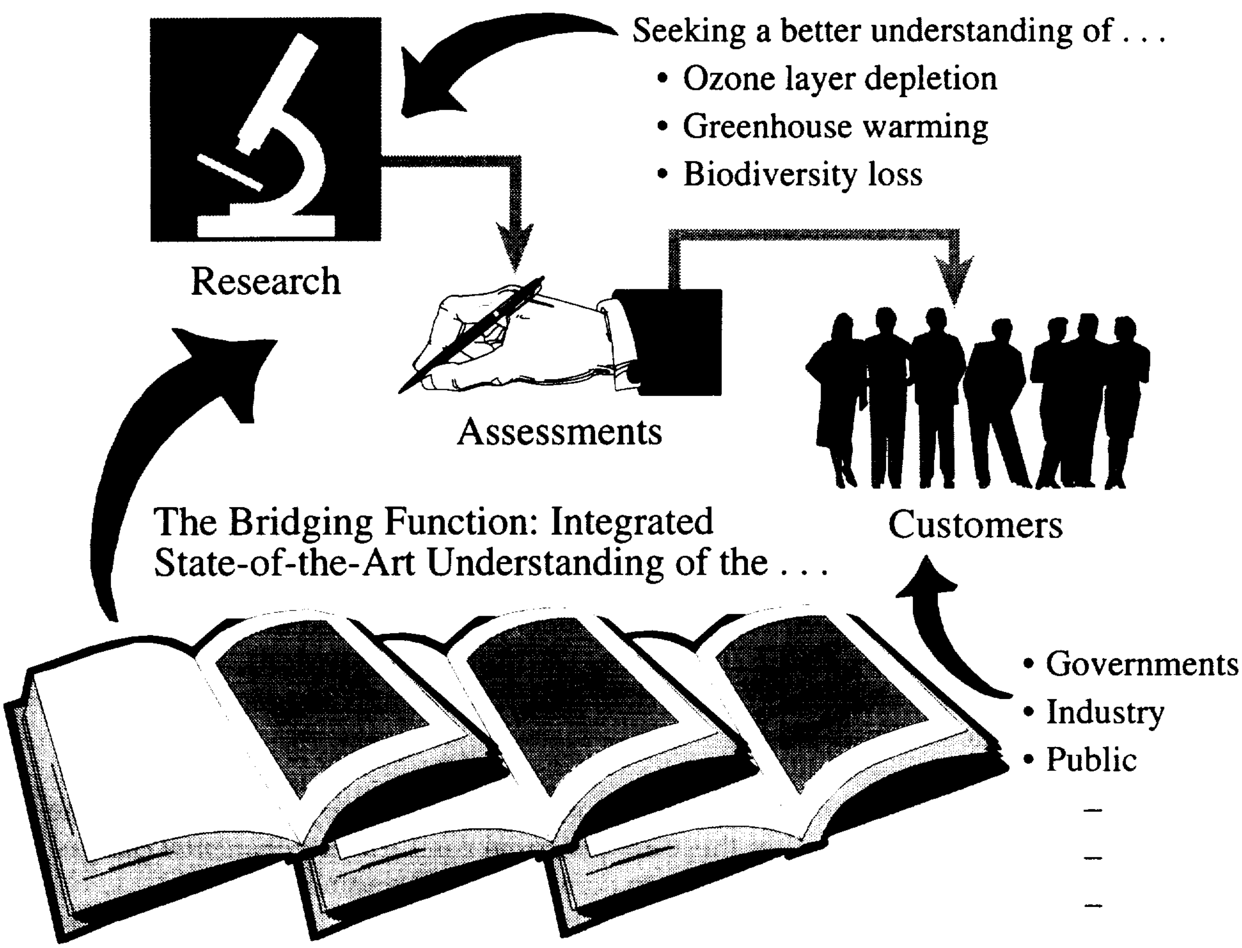

Figure I-C-1. The End-to-End Process of Research, Assessment, and Decision Making

those who create the information (the expert communities) and those who make decisions based upon that information (the policy making communities).

Several features of such assessments are relevant:

- They are the integrated perspective of the (vast) *majority* of the expert communities involved, which is in contrast to the more limited utility of the viewpoint of a particular scientist, technologist, or economist.

- They are the perspective of the *global communities*, which is in contrast to a particular national or industrial-sector viewpoint.

- They are an *end-to-end picture* of the issue (causes -> effects -> options), which is in contrast to a study of a single aspect of an issue (e.g., the atmospheric impact of CFC replacements).

- *Several such assessments have been done* by relevant expert communities to serve as input to policy decisions (all currently in various stages), e.g.

  > Assessments, since 1981, of the three Ozone Science, Effects, and Technology/Economic Panels of the United Nations Environment Programme (UNEP) and/or the World Meteorological Organisation (WMO), which now provide input to the 1987 U.N. Montreal Protocol on Substances That Deplete the Ozone Layer.

  > Assessments, since 1990, of the Intergovernmental Panel on Climate Change (IPCC), whose three Working Groups provide input to the 1992 U.N. Framework Convention on Climate Change (FCCC).

  Appendix C contains further information on these panels, working groups, and decision making bodies, which differ from each other in a number of respects.

- Knowledge improves over time; hence, *the assessment process is one of periodic updates of understanding*, as both the Montreal Protocol and the Climate Convention have recognised, with major assessments having been requested on about 3- and 5-year intervals, respectively, with *ad hoc* interim reports between assessments on special topics.

- Correspondingly, based on these assessments and other inputs, the *decision making process is also periodic.* For example, the Montreal Protocol has been amended or adjusted three times. (The Climate Convention, which is much newer on the scene, does not have a Protocol or equivalent, although debate regarding such a policy instrument is under way.)

- Assessments generally have been done issue by issue; i.e., on ozone-layer depletion or on greenhouse-forced climate change.

- But more and more, it is being recognised that *issues are coupled*; e.g., ozone depletion causes a cooling tendency on the climate, as does particulate matter from surface air pollution. As a response, the assessment processes have tried more and more to work together, e.g., a common radiative forcing chapter in both the UNEP/WMO ozone-depletion and IPCC climate assessments.

- The *environmental impacts of aviation* is a new example of how a single type of perturbation is coupled to several phenomena and issues; hence, it affords an opportunity to carry out a higher level of integration scientifically, technologically, and with respect to policy decisions.

D. Aviation Regulatory Context

Historically, the environmental issues associated with aviation have been local ones: airport noise and air pollution. These phenomena have been studied by experts, options developed, decisions taken, and restrictions applied. Because aviation is global, the decisions and actions understandably have been international in nature, i.e., nations jointly deciding upon common measures adopted by all members; namely:

- The international body that has served historically for such decision making is the U.N.'s *International Civil Aviation Organization (ICAO)*, now composed of 184 contracting States.

- ICAO has set Standards on (i) *noise during takeoff and landings* and (ii) *engine emissions that are involved with local air quality* - NO_x, CO, HC, and smoke. These decisions have influenced the engine and aircraft designs of the world's aviation industry ("New aircraft or engines shall not emit more than ..."), as well as operations at most airports.

- The ICAO body that is responsible for recommending environmental standards for aviation is the *Committee on Aviation Environmental Protection (CAEP)*, which consists of experts from 15 member States and observers from interested communities (e.g., airlines and manufacturers). The Committee has three working groups: noise, airports and operations, and emissions. The emissions working group of CAEP has critically assessed global three-dimensional inventories of aircraft engine emissions, assembled relevant data bases, and keeps under review technology developments and environmental impacts that might bear on revision of existing Standards or establishment of new ones.

E. Broader Public Policy Context

We are at a point where environmental issues that are shared by most nations have not only been commonly recognised, but have been assessed by the empowered world-wide expert communities, resulting in joint decisions by international regulatory

bodies, e.g., airport noise and emissions and ozone-layer depletion. Further, the process is underway for the issue of climate change.

As noted, there are initial (but nevertheless clear) signs of the recognition by the research/assessment/decision making processes that "It is one atmosphere." The aviation issue represents one such example:

- The Montreal Protocol, even though its major regulatory focus is on halocarbons, has requested, over the past two cycles, *assessment of other ozone-depleting sources*, such as aircraft, space shuttles, and rockets. Further, at their Seventh Meeting in December 1995, the Parties to the Montreal Protocol requested an updated and expanded assessment of the impacts of aircraft emissions, working as appropriate with ICAO and IPCC.

- The *quantitative focus* on aviation by the Climate Convention thus far has been on establishing the appropriate means of allocating aviation fuel usage for international flights among nations (e.g., for an Air India flight from New York City to London). But, the Conference of the Parties to the Convention noted, in April 1995, that the "allocation and control" of international aviation emissions should be addressed by the Convention's technical and scientific subsidiary bodies, taking fully into account ongoing work in governments and international organisations including ICAO.

- In 1995, ICAO requested assistance from IPCC and the Montreal Protocol's Ozone Scientific Panel in assessing aviation's global impact on the atmosphere.

- The bottom line of the above points is that the need for an integrated international assessment of our current state of understanding of the global environmental impact of aviation is recognised. Furthermore, despite the multi-issued complexity of aviation impacts, there are several reasons to be optimistic about the feasibility of providing decision makers initial information in a useful "user-friendly" format:

  > A substantial body of research has been steadily clarifying the atmospheric role of aircraft with an expanding set of findings and results.

  > Consolidation review reports on those results are underway by the sponsoring research organisations.

  > Considerable experience with assessments exists in the atmospheric research community.

  > Much that has been done already in the ozone-depletion and climate-change assessments bears upon the aviation issue and thereby need not be repeated, e.g., the human-impacts characterisation of increases in ultraviolet radiation and the changes in the climate system, and provide a means for an aircraft assessment to link to an established end-to-end process.

II. Scientific and Technological Sessions of the Symposium

A. Aircraft, Engines, and Emissions

Background

The aircraft engine manufacturers' goal is to provide value to their customer in terms of direct operating costs, operability, reliability and emissions. The primary context in which they operate is one of competitive market forces. For example, fuel economy has been a high priority with both airlines and manufacturers, not only because of its impact on direct operational costs but also because of range and payload implications. This has resulted in engine technology trends to higher engine pressure ratios, with concurrent core temperature and pressure increases, together with the development of the turbofan engine, having progressively higher bypass ratios.

The original stimulus for control of aircraft emissions arose from local air quality issues at and around airports. This led to the establishment of Standards by ICAO and their implementation by various national certification authorities. The continued growth of air traffic, together with the concern over the global atmospheric effects of aviation emissions, has resulted in pressure, not only for greater stringency of existing Landing/Take-off (LTO) Standards, but also for control of emissions during other phases of flight, in particular climb and cruise. Whilst the focus has been on NO_x emissions, because of the direct effect on atmospheric ozone in the upper troposphere and lower stratosphere, other currently unregulated constituents, e.g., particulate, CO_2, water vapour, sulphur compounds, are also under scrutiny by the atmospheric science and climate communities.

The summaries and Key Points from the presentations and ensuing symposium discussions regarding aircraft, engines and their emissions are as follows:-

Engine Performance

The modern high performance gas turbine ("jet") engine used to power typical commercial civil aircraft is essentially a continuous flow heat engine, operating at constant pressure, using air as its working fluid to generate thrust to propel the aeroplane through the air.

The operating cycle comprises 3 main stages:

- compression of the ambient air, with consequent increase of temperature and pressure;

- introduction of fuel (aviation kerosene) into this air and combustion to increase the temperature of the air still further;

- expansion and consequent cooling of the combustion gases through the turbine to extract energy to drive the compressor.

These lower temperature gases are then expanded, i.e., accelerated, further through the engine exhaust nozzle to generate propulsive thrust from the change in momentum of the air.

The efficiency of the conversion of the fuel energy into kinetic energy (by combustion) is known as the thermal efficiency, which is determined by the engine cycle pressure ratio and combustion temperature. Increases in these raise the efficiency, but are constrained by thermal and mechanical limitations of the turbine system.

The conversion of the kinetic energy into real propulsive work is known as the propulsive efficiency. Since this is momentum related, either or both air mass flow and velocity may be increased or traded-off to achieve efficiency improvements. Moving a small mass of air at high velocity can have the same efficiency impact as moving a larger amount more slowly. Early jet engines were designed on the former basis - and generated lots of noise! Modern engine designs use the 'bypass' principle to move very large masses of air at lower overall velocities to achieve quiet engines, which are propulsively more fuel efficient than the older engine designs. There is, however, a limit on the effect of increasing the bypass ratio as inherent greater engine diameters lead to increased weight and drag of the engine and diminishing returns on specific fuel consumption (SFC), the rate of fuel flow/unit of thrust.

Figure II-A-1 indicates the cruise specific fuel consumption improvements with trends in engine performance cycles over time. Since the first jet engines, thermal and propulsive efficiencies have improved significantly. Improvements are still possible - as indicated by the line for limiting thermal efficiency - but the rate of change has slowed considerably and is levelling out - even though fuel efficiency is one of the commercial pressures for the aviation industry - and is a measure of the technical and economic difficulties facing the manufacturers.

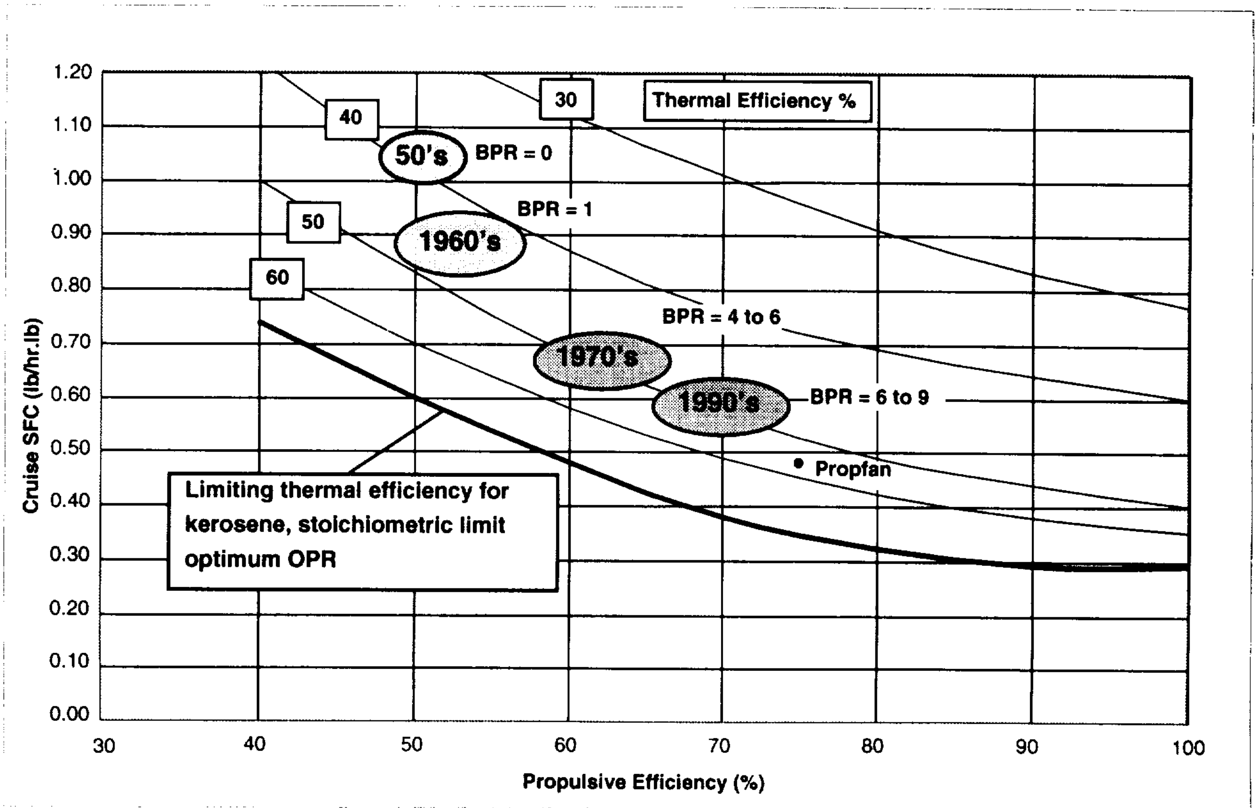

Figure II -A - 1 Engine Performance Cycle Fuel Efficiency Trends (Rolls Royce plc)

Emissions

Engines produce CO_2 and H_2O as the major direct products of combustion, together with small quantities of other emissions; hydrocarbons (HC), carbon monoxide (CO) and carbon soot (smoke) as products of incomplete combustion, sulphur oxides (SO_x) from the sulphur in the fuel and oxides of nitrogen (NO_x) as a result of high temperature reactions of air. The source of these emissions is, of course, the engine combustion system. HC and CO are primarily produced at low power conditions, whereas the smoke and NO_x are mainly generated at higher power.

A third efficiency definition is that of combustion efficiency, i.e., the completeness of the chemical conversion of fuel into products (CO_2 and H_2O for a hydrocarbon fuel). This is controlled by the combustion temperature, pressure and residence time. For modern engine designs, combustion efficiencies are better than 99.9% at high powers and at least 98.5% at low power (idle) conditions. The inefficiencies appear as unburnt or partially degraded hydrocarbons, CO and soot (carbon).

Combustors of modern engines consist of annular configurations and the design and technology of these has evolved steadily over the last few decades. As a result, these combustors meet a long list of diverse and demanding performance, operability, durability and overall reliability requirements. In addition, technology to reduce the HC, CO and smoke emissions of these combustors to very low levels has been developed and incorporated into operational engines.

As a consequence of the advances in the control of these emissions, the emphasis has primarily focused, for at least the last decade, on control of the oxides of nitrogen. However, there are conflicting demands. Better thermal efficiency results in improved fuel consumption, but also leads to higher combustion temperatures and pressures, which themselves generate higher levels of NO_x. Thus there is a need for technology improvements - even to "stand still" at a constant NO_x level. Figure II-A-2 shows the achievements so far.

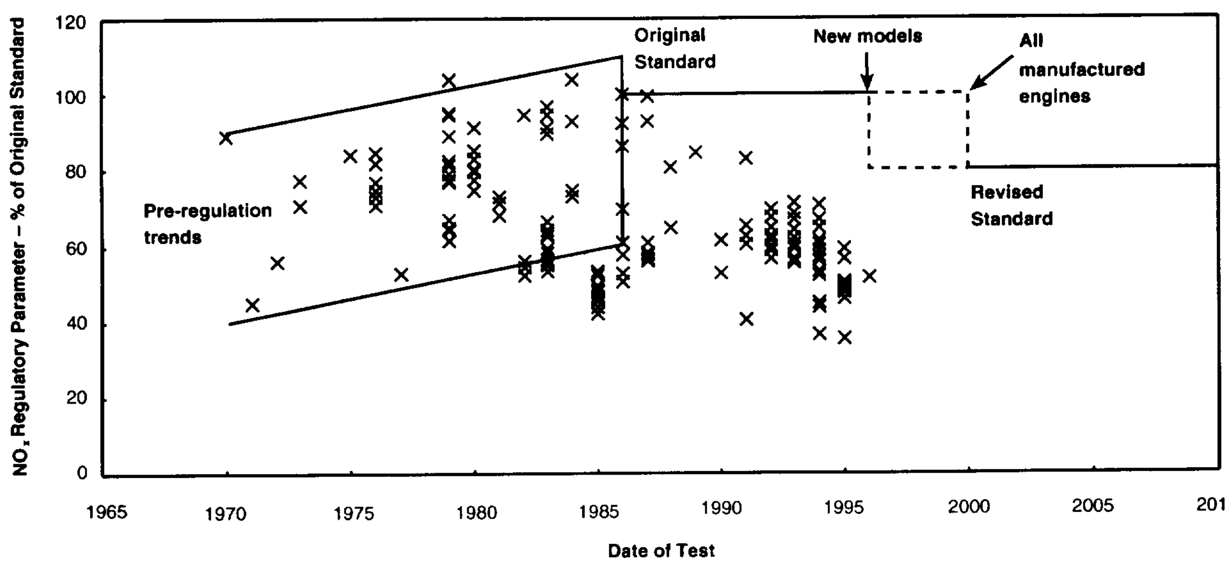

Figure II - A -2 Turbofan NOx emissions

There are continuing extensive efforts to develop and incorporate combustors with reduced NO_x levels, not just for subsonic aircraft engines, but also for prospective future second generation supersonic aircraft (section IIIA).

Certification Requirements

ICAO's Annex 16, Volume II, "Aircraft Engine Emissions" sets out internationally agreed Standards for the control of emissions in the vicinity of airports. This document also lays out the details of test and measurement procedures, calculation methodologies and statistical compliance factors. Not having the force of law, with regard to its implementation, the Annex relies on national implementation (e.g., FAR,

Part 34 in the USA, BCAR-M in the UK). However, signatories to the Chicago Convention, i.e., most States, are legally obligated to comply or to file formal notice of difference.

These Standards apply to engines only, not to the whole aircraft, and are meant to control HC, CO, NO_x, smoke and fuel venting, for a reference Landing and Take-off (LTO) cycle up to an altitude of 3000 feet (915m). They require type testing of a very limited number of engines to determine compliance with the Standards and do not demand any in-service testing to demonstrate continued compliance.

The Annex also defines the test fuel specification, including a limit on sulphur content (0.3%). The average sulphur level in jet fuel is typically only 0.04 - 0.05%. There are arguments for total removal, because of its potential for atmospheric aerosol formation. However, this is a costly issue since aviation fuel is only a small fraction of refinery output and would require special treatment. Sulphur in fuel currently serves a valuable function of lubrication in the fuel system. If regulation required removal of all sulphur, then another agent would have to be used, at an additional cost. It is relevant to assess what level can be environmentally acceptable. Ultimately, a proper cost/benefit study would be needed.

For the future, there will undoubtedly be continued pressure for more stringent LTO Standards. In addition, since aircraft spend the largest proportion of time and produce most of the emissions during the climb and cruise phases of flight, there is pressure for Standards relating to these conditions. Although an improvement in the LTO cycle emissions should be reflected in better performance at cruise, the relative improvement may vary between engine types. It is also important to ensure that the correct constituents are being targeted and with the right balance.

For flight conditions, it is possible to provide accurate data for CO_2, H_2O, SO_x, HC, CO, and NO_x, either from a knowledge of fuel consumption, by measurements of engine emissions or by prediction. Measurements are best taken in an altitude simulation facility. This is very expensive, which weighs in favour of prediction if possible.

There is a particular shortfall in our understanding of the generation of specific hydrocarbons, other nitrogen compounds and particulate matter. In addition, there is a lack of reliable methods for either measuring or predicting them at this time.

Any future second generation supersonic aircraft may have specific different issues to face because of the altitude at which they would fly. There are already significant atmospheric and technology research programmes attempting to define, quantify and mitigate adverse impacts.

Certification methodologies and Standards will need to be developed if there is a need for control of in-flight emissions from either subsonic or supersonic aircraft. For example, it may be more relevant to certificate aircraft rather than engines since the

total aircraft design dictates the operational aspects, i.e., cruise altitude, speed, power requirements, that determine the emissions output to the atmosphere. Consideration of the emissions on an aircraft basis may need to include productivity, for example the relative performance expressed as an emissions output per seat - kilometre. Given the different context of concerns regarding in-flight and LTO cycle emissions (global versus local), a Standard for control of in-flight emissions may have a form which is substantially different from that currently used to regulate LTO emissions (mass of emission per unit of thrust). This may lead to conflicting technological/operational solutions. Any such conflicts between these requirements will need to be minimised.

Key Points

1. *There is on-going engine design progress towards improved fuel efficiency and reduced emissions, in a context of broadening environmental concerns.* The manufacturers need clear guidance on the priorities for emissions reduction to support future engine designs, but the scientific community cannot yet provide definitive statements of need. As other sources are being targeted and constrained, aviation with its growth expectations will increasingly stand out.

2. *The setting of emissions certification Standards takes into account the engine-to-engine variability.* The statistical factors used in the calculation of characteristic regulatory levels were developed on the basis of 90% confidence that the mean of the total production of an engine type would comply with the emissions Standard.

3. *Performance and emissions deterioration with age has not been fully quantified, but is believed to be small.* Typical airline practice is that even a small decrease (2%) in engine fuel efficiency is likely to trigger a full or partial overhaul to try to restore lost efficiency.

4. *ICAO/CAEP (Committee on Aviation Environmental Protection) is proactively addressing the topic of aircraft engines and emissions.* At the CAEP/3 meeting in December 1995, there was a majority recommendation for a tightening of the ICAO NO_x Standard. This is currently being considered. CAEP's work programme for the next 2-4 years includes on-going studies of technical developments in emissions abatement, engine performance, measurement/prediction methodologies, the possibility of certificating aircraft not just engines and the impact of operational practices on fuel efficiency and emissions.

Principal contributors to the session on Aircraft, Engines and Emissions

Roger Cottington:	Session Chair
Tony Fiorentino:	Rapporteur
Don Bahr:	A tutorial
Jim Elwood:	Current certification requirements
Dave Lister:	Future certification requirements
Joel Levy:	Provocateur

B. Emission Inventories: Current and Future

Background

A major driver of the environmental concerns about emissions from aircraft is not so much the burden from the current fleet but the potential future burdens, in view of the historic rapid expansion and projected continuing high future growth rates. Typical traffic forecasts (1992 base) are for a tripling in 25 years and a sevenfold increase in 50 years. On an available seat kilometre (ASK) basis, both fuel use/ASK and NO_x /ASK are typically anticipated to decline (Figure II-B-1), due to increased engine efficiencies and combustion technology changes. In the context of these trends, atmospheric modellers need reliable global, 3-D, aircraft emission databases or 'inventories' for a base year and at times in the future in order to evaluate potential impacts from aviation alongside other inputs.

Two global inventories have been developed in recent years, one in Europe (ANCAT/EC) and the other in the USA (NASA). These are in widespread use by modellers. Both incorporate an extensive traffic database - derived primarily from air traffic control data (ANCAT/EC) or airline time-tables (NASA) - for their selected base year (1990/1992), idealised flight operations assumptions and a methodology for prediction of emissions over an entire flight cycle. Both inventories cover civil and military activity, take account of seasonal variations in air traffic and provide detailed 3-D information on fuel use and NO_x emissions; the latter inventory has been extended to include HC and CO emissions.

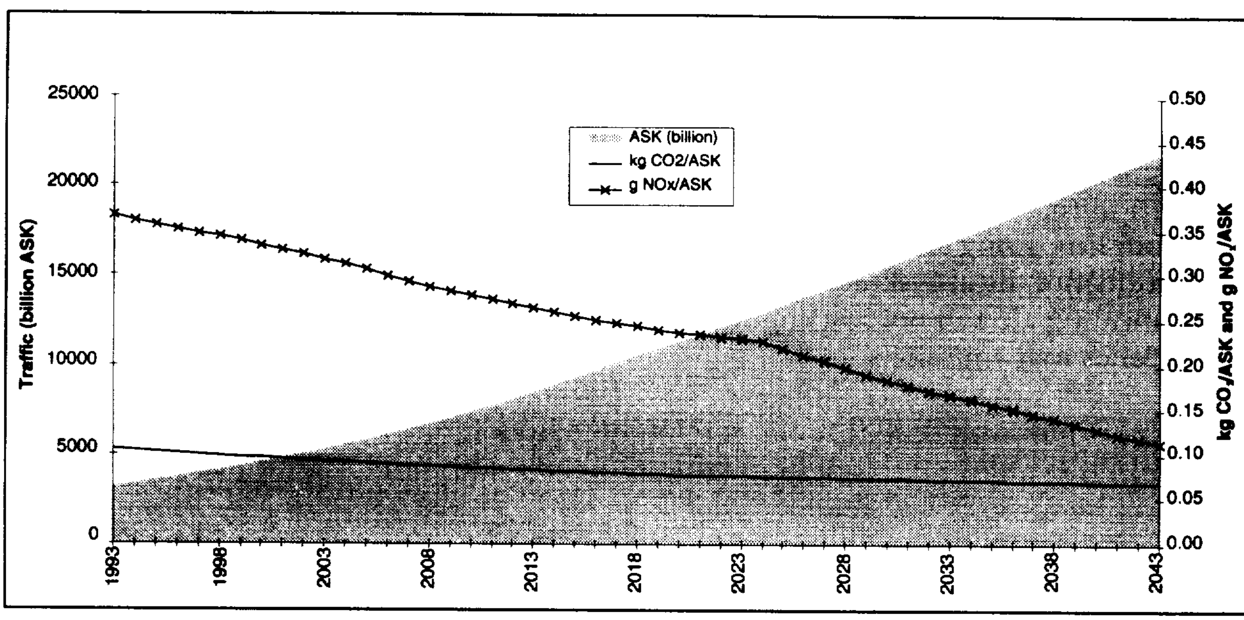

Figure II - B -1 Trends in Traffic and Emissions (UK Department of Trade and Industry)

Neither inventory includes any indication of the tropopause height, nor its variation with season. This information is available from other sources and is applied by modellers to determine whether emissions are in the troposphere or stratosphere.

Initial versions of these inventories were extensively reviewed and analysed within the CAEP process. There were large differences in many areas of the early inventories, but having two inventories, using different conceptual approaches in key areas, was of great benefit in identifying uncertainties, errors and defining paths for improvements.

More recent updated products, both of which use 1992 as their base year, appear to be in very good agreement for fuel consumption and NO_x emissions from civil aviation, which probably accounts for at least 80% of the fuel consumed by aircraft.

Data from actual airline operations and from research programmes making cruise emission measurements using chase planes or in altitude simulation test facilities, have provided valuable confirmation of the calculation procedures used for prediction of in-flight emissions from individual aircraft/engines and of global inventory predictions. While further data would be desirable, there is already a high level of confidence in the use of these procedures for civil aviation.

The assumptions of idealised flight operations, i.e., great circle routing, optimum aircraft flight altitudes and speeds, no ATC delays, no winds or adverse weather factors, etc., imply that the overall fuel burn and emissions are likely to be minimum values. Some parametric studies are aiming to quantify the consequences of operational realities. Initial indications are that each of these factors has the potential to change the fuel burn, and hence emissions by a few percent. Of course, calculation of the overall integrated effect on the world fleet would need a complex summation of all of these variants - a task which is probably not justified at this time, in light of much greater uncertainties elsewhere.

The military components of these inventories have been very difficult to define in terms of type and extent of operations, due mainly to the reluctance of military authorities to release data. The ending of the Cold War has not significantly altered the uncertainties and there are substantial, unresolved differences between the two inventories. However, the impact of these differences is probably small in comparison with the total impact of civil aviation.

It is also clear that there is a significant shortfall (>10%) between the total aggregate of the fuel in the inventories and the figures published by the International Energy Agency for world production of refined jet fuel. However it is known that not all fuel declared to be aviation jet fuel is actually sold or used as such.

Further comparative studies of these issues are expected to provide a good understanding of the sources of the discrepancies. However, the differences in the inventories are considered to be relatively small in comparison with the uncertainties relating to other sources, e.g., lightning, and global modelling limitations.

Future forecasts are focused on 2015 - about 20 years hence. Within this timescale, which matches the lifetimes of aircraft and engines, emissions predictions can sensibly be based on extrapolations from current technology, supplemented with options for introduction of second generation supersonic civil aircraft in the latter part of this time frame. Historical inventories generated from known traffic and aircraft technology provide trend information to support these future projections.

European and US efforts have approached the production of forecast 2015 inventories in different ways, but there is fairly close agreement in the totals of fuel consumed but greater divergence of the NO_x totals. Forecast datasets will continue to be reviewed through the CAEP process, alongside the 1992 base year inventories.

Beyond this time frame, top-down emissions NO_x burden scenarios have been developed in the UK as a policy tool (Figure II-B-2). Results suggest that the global NO_x burden due to aircraft is expected to lag well behind the growth in traffic. Continued improvements in fuel efficiency and the development of new NO_x reduction technologies will significantly restrain emissions increases and could lead to a levelling off of emissions towards the middle of the next century. Further efforts are being put into developing these types of tools.

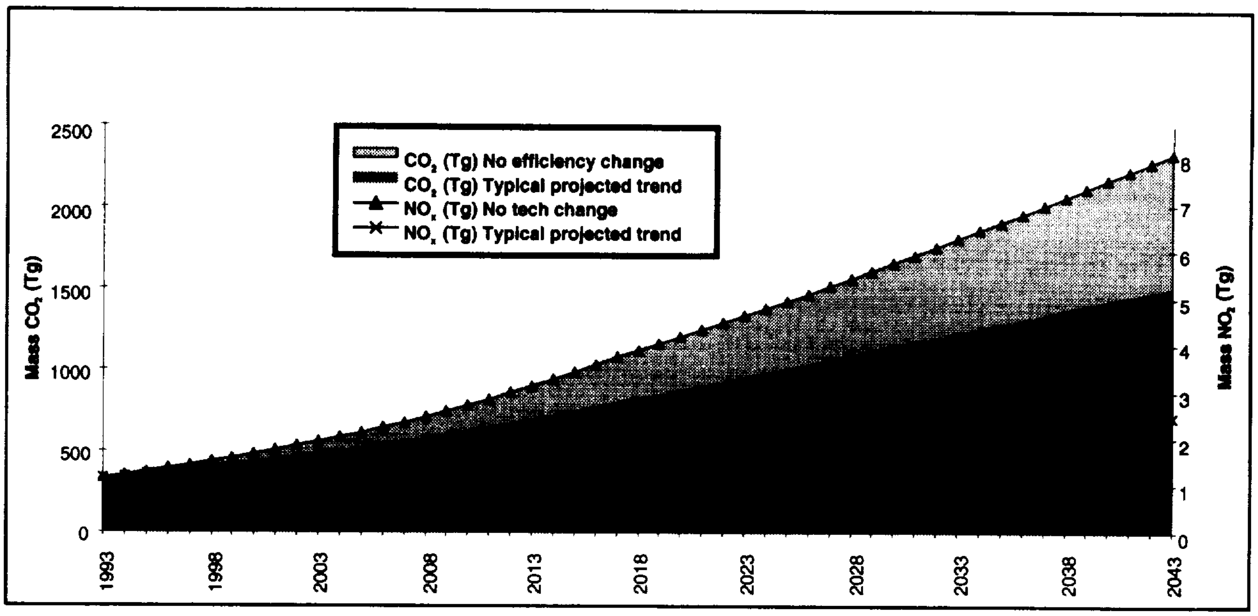

Figure II - B -2 Long Term Trends in Emissions from Aviation (UK Department of Trade and Industry)

Key Points

1. *Two major 3-D global emission inventories are available on a 1° x 1° x 1 km grid basis for a base year of 1992. Both contain fuel consumption and NO_x emissions, one also includes HC and CO emissions.* They are ideal in the sense that they are based on optimised flight operations assumptions. They take account of seasonal air traffic variations, but do not include information on tropopause height, or its seasonal variation. Such information is available elsewhere and allows assignment of emissions to the troposphere or stratosphere.

2. *The agreement between the inventories is very good for civil aviation, which accounts for at least 80% of the total fuel burn.* The differences are probably equivalent to 2-3 years traffic growth.

3. *For military aircraft there are bigger differences, due to the lack of reliable operational and technical data.* These differences are not likely to be significant in the overall picture.

4. *The uncertainties in the aircraft NO_x emission inventories are much smaller than those of other sources, e.g., lightning, convective plumes, or of model abilities to calculate impacts.* It seems that knowledge of aircraft NO_x inventories is not the limiting factor in accurately predicting ozone impacts for the next few decades.

5. *Inventories probably need to be extended to incorporate other species of atmospheric relevance.* Particulates and aerosols appear to be important. At present there are only "smoke numbers" and these are not adequate for calculation of impacts.

6. *Studies of some other sensitivity issues, e.g., routing, meteorology, are required.* These would aid assessment of the magnitude of the differences between the fuel use and emission burdens calculated from the idealised inventories and those generated by real operational practices.

7. *Development and improvement of 25 year forecasts and longer term scenarios is underway, incorporating both subsonic and potential supersonic aircraft.* Historical inventories will provide a means of validating forecasting methodologies and atmospheric models.

Principal contributors to the session on Emission Inventories

Uppli Wickrama:	Session Chair
Tony Fiorentino:	Rapporteur
Malcolm Ralph:	Overview
Roger Gardner:	ANCAT review
Alf Schmitt:	ANCAT review
Steve Baughcum:	NASA review

C. Stratospheric Ozone Layer Depletion: The Original Issue

Background

Stratospheric ozone depletion is not a theory but a fact. The Antarctic ozone hole is a dramatic, indisputable evidence for the depletion. Ozone depletions in other regions of the stratosphere, though less dramatic, have been recorded. Ozone losses have been observed over the past few decades and the extent of ozone depletion is dependent on location, season, and year. Attributing the ozone changes to specific causes, and predicting the future levels of stratospheric ozone, is a major area of research and has important consequences to society.

Ozone in the stratosphere is the shield that protects the biological system on the Earth's surface from the damaging ultraviolet (UV) radiation (i.e., radiation in the wavelength range of 290 to 320 nm). Absorption by ozone changes by many orders of magnitude in going from the harsh UV to the visible radiation. Therefore, the fractional removal of the UV radiation by ozone is different at different wavelength. While ozone completely filters out surface radiation at wavelengths less than approximately 290 nm, a fraction of radiation at longer, biologically active, wavelengths are allowed to reach the surface. The fractional change in the radiation level is much higher than the fractional change in the ozone column abundance in the stratosphere; it may be up to a factor of ten, depending on the wavelength, for a change of 10%. Enhanced biologically active UV radiation has been linked to skin cancer, changes in biological activity (human immune suppression, plant and ecosystem damage, ...), and alterations in the composition of the troposphere. Therefore any alterations in stratospheric ozone abundance caused by human activity is of great concern.

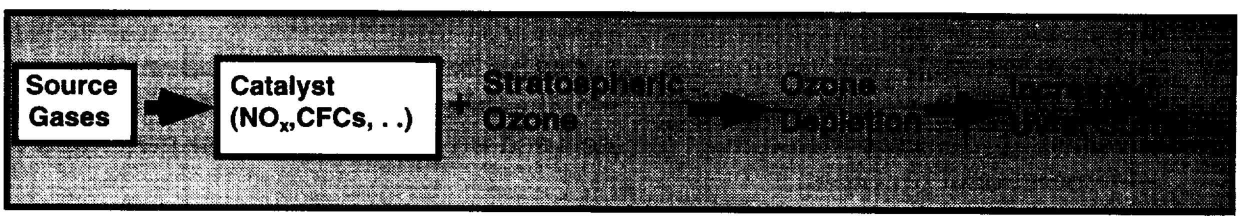

Figure II-C-1. The Stratospheric Ozone Depletion Issue

In addition to its role as a UV filter, ozone also acts as a greenhouse gas. Its efficiency in this regard depends on altitude and latitude. Earth's climate can be affected by changes in the total amount of ozone as well as its vertical distribution. The understanding of climate effects is still emerging and is not as well established as the connection between UV and overhead ozone levels. As noted later, the effects of aircraft emissions are largest in the lower stratosphere, where ozone is most fragile and climate consequences are most pronounced.

The majority of atmospheric ozone (i.e., about 90%) resides in the stratosphere. Here, the harsh UV radiation necessary to break molecular oxygen (O_2) bond is available to generate oxygen (O) atoms. These atoms combine with molecular oxygen to form ozone. However, the same oxygen atoms also react with ozone to destroy it. Thus, there is a simple dynamic balance between the production and destruction of ozone which leads to a steady state

abundance of this UV absorbing species. This is the basic theory of Chapman, which explains the presence of ozone in the Earth's atmosphere.

Approximately 30 years ago it became apparent that the above mechanism could not quantitatively account for the amount and distribution of ozone in the stratosphere. Over the past decades, the role of hydrogen oxides, nitrogen oxides, and halogen oxides and the atmosphere transport in controlling the amount of ozone has been recognised. The basic concept behind this development is the catalytic nature of the chemical cycles involved in the destruction of stratospheric ozone. The catalytic cycles enable one molecule of the emitted species to destroy thousands of molecules of ozone, via chain processes, before being removed from the stratosphere. Thus, it has become possible for seemingly minor human activities to alter stratospheric ozone by substantial amounts.

In addition to improvements in our understanding of the chemical processes that control stratospheric ozone abundance, our knowledge of the role of transport in distributing ozone and affecting the relative ability of chemical processes to change the concentrations has also been developed. It is now known that the majority of stratospheric ozone is produced in the tropical stratosphere and moved poleward and downward. There is a delicate and dynamic balance between the rates of production, transport, and destruction which together dictate the amount of ozone in a given region of the stratosphere. A quantitative understanding of this dynamic balance is the key to predicting the future levels of ozone and, specifically, the effect of aircraft emissions on the abundance of ozone.

The rates of ozone production and destruction in the upper and mid-stratosphere in the tropical regions, where most of the ozone is made, are quite large. In the mid- and high-latitudes, the ozone production rate in the lower stratosphere is much smaller: higher the latitude and lower the altitude, the smaller the production. The majority of ozone in this region is brought in from the ozone-production locations. Therefore, an increase in the ozone destruction rate in these regions will have a major effect on the amounts of ozone. This fragile region is exactly the one which would be traversed by a large fraction of the proposed supersonic aircraft and some of the current subsonic aircraft during colder seasons.

We now know that there is a synergism between the roles played by nitrogen oxides, halogen (i.e., chlorine and bromine) species and other stratospheric constituents. This synergism leads to differing effects of aircraft emissions as the levels of halogen species in the stratosphere change. It has also become clear that other factors not influenced by humans, such as volcanic eruptions, have a major effect on the magnitude to the perturbations due to human activities.

In the past decade there has been a large increase in our understanding of the chemistry of ozone in the stratosphere. The major changes are the recognition of the role of heterogeneous reactions and a better representation of transport. These two changes have dramatically altered the predictions of the effects of supersonic aircraft compared to those made in the 1970's, where heterogeneous reactions were not included in the assessments and 1-D models were used to predict the changes. Yet, quantitative predictability is not firm. At the same time, international agreements have effectively defined acceptable levels of ozone changes due

to the chlorofluorocarbons (CFC) and other human made halocarbons. Recent agreements under the Montreal Protocol control halocarbon emissions that would deplete ozone by less than 1%. This session addressed the role aircraft will play in altering the ozone layer in the current as well as the future atmosphere.

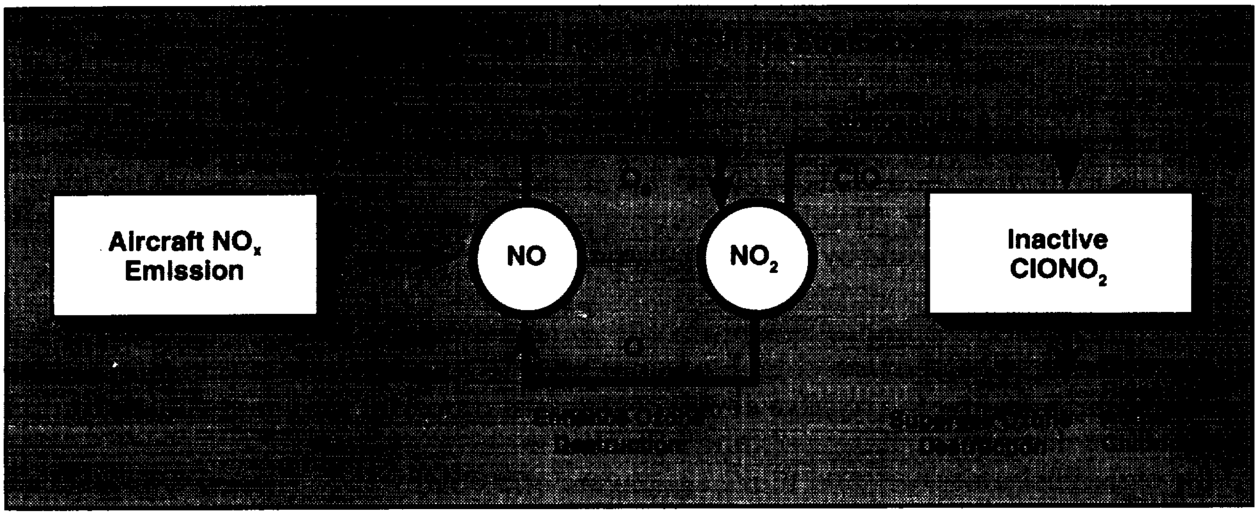

Figure II-C-2. Aircraft and Stratospheric Ozone Depletion Chemistry

Key Points

The key points and uncertainties that emerged from the ensemble of talks and subsequent discussions regarding the effects of aircraft on the stratosphere are given below. They are not an assessment of the problem and are not presented in any order of priority or concern.

1. *The main features of photochemical stratospheric ozone loss are understood.* The ozone loss in the upper stratosphere has been observed and can be "quantitatively" accounted for by the increase in CFCs and other human produced halocarbons. The polar ozone loss is also understood. The mid-latitude lower stratospheric ozone depletion, though not completely understood, has been clearly connected to the increases in chlorine and bromine. The levels of chlorine, nitrogen oxides, water vapour, and sulphuric acid aerosol and the stratospheric temperature are the major factors which determine the extent of ozone depletion.

2. *Nitrogen oxides from aircraft is one of the primary reasons for the concern with respect to supersonic aviation in the stratosphere.* Nitrogen oxides in the stratosphere can deplete ozone via catalytic reactions that are extremely efficient in the mid- and upper-stratosphere.

3. *Water, particles, and sulphur emissions alter the effectiveness of NO_x emissions.* The increase in particulate matter, either via direct emission or via generation from the emitted sulphur compounds, can enhance the surface area for heterogeneous reactions. The increase in

water vapour may also enhance the available surface area and the reactivity for heterogeneous reactions. Moreover, they can convert aircraft-emitted nitrogen oxides into inactive forms and activate chlorine species. Therefore, release of sulphur compounds, particulate matter, and water vapour by aircraft are also of concern.

4. *Nitrogen oxides in the stratosphere can both enhance and curtail ozone depletion.* Nitrogen oxides play dual, almost opposing, roles in the stratosphere, depending on where they are located. In the lower stratosphere, nitrogen oxides inhibit the ozone destruction by chlorine compounds and in the lowest parts also lead to photochemical ozone production. In the mid- to upper-stratosphere, they actively destroy ozone. Therefore, the role of nitrogen oxide emissions in changing ozone levels depends on the location of the injection, transport from one region to another, the levels of particulate emissions, the future levels of aerosols and the future levels of chlorine in the atmosphere.

5. *The effects of nitrogen oxides do not persist in the stratosphere.* The duration of nitrogen oxides in the mid and lower stratosphere is the same as the turn-over time of this region. Therefore, once transported into the troposphere and removed via deposition, the effect due to nitrogen oxides will not persist. Therefore, a cessation of nitrogen oxide emissions should restore the stratosphere to its initial state within a few years, barring other major changes.

6. *Heterogeneous reactions play critical roles in changing the concentrations of stratospheric ozone.* The presence of sulphuric acid aerosol particles and polar stratospheric clouds converts reactive nitrogen species into inactive forms and inactive chlorine compounds to active form via heterogeneous reactions. The enhanced understanding of these reactions is one of the fundamental reasons for the differences in effects of supersonic aircraft predicted in the 1980s and today. The role of heterogeneous reactions has been amply substantiated by the observed changes in ozone levels and partitioning between nitrogen oxides following the eruption of Mt. Pinatubo.

7. *The lack of information on the atmospheric transport of chemicals has hindered better prediction of the effect of aircraft on the stratosphere.* The motions of the air in the stratosphere and between the stratosphere and troposphere are poorly understood. Therefore, it is difficult to quantify where the effluents of aircraft will go and how long they persist. Different 3-D chemical transport models give different results. Simplified "synthesis" pictures of the complex processes of transport, such as the tropical pipe and diffuser models, have been developed, but may not be adequate for evaluation of the effects of aircraft. Uncertainties in the dispersion and transport of aircraft exhaust is one of the major reasons for the uncertainties in the understanding of the effects of aircraft. The transport, both horizontally and vertically, is all the more important because of the dual role of nitrogen oxides mentioned above.

8. *The effects of proposed high-speed civil transport (HSCT) on stratosphere may be estimated, albeit with very large error bounds, if chlorine and aerosol loading is known.* The chemical impact of the supersonic aircraft-injected nitrogen oxides can be estimated. The uncertainties associated with the estimations of the impact of aircraft-injected nitrogen oxides may be

currently too large for policy decisions. The uncertainties arise from the poor understanding of the transport, the state of the future atmosphere, laboratory data, and the ability to model certain fundamental processes. Of these factors, our understanding of the transport is a clearly identified uncertainty. Future climate changes in the stratosphere and alterations in the concentrations of key constituents such as H_2O, CO_2, and CH_4 (methane) are the other key factors. Qualitatively, as the level of chlorine in the stratosphere decreases, a given amount of NO_x will lead to a larger ozone loss. The estimates of the ozone depletion for the next century are expected to become more accurate with further refinements due to the ongoing research programs.

9. *Most model simulations predict an ozone depletion due to supersonic aircraft.* The 2-dimensional models currently predict column ozone depletion of up to 0.5 % for 500 aircraft flying in the lower stratosphere with the current levels of chlorine if the emission NO_x is 5 g equivalent of NO_2 per kg fuel (i.e., EI = 5). Such NO_x emission levels are expected from advanced low emission combustors. These predictions must be qualified because the 2-dimensional models' inability to adequately represent the atmosphere. However, depletion of ozone due to HSCTs are expected to be less than a few percent, not an order of magnitude larger as originally projected. Because of the large uncertainties, even the upper bounds may also be somewhat soft.

10. *Subsonic aircraft may substantially affect the level of ozone in the stratosphere in the future.* Currently, it is believed that the subsonic aircraft flying in the troposphere do not affect stratospheric ozone levels. Yet, the effects of subsonic aircraft is a concern because a fraction of the current subsonic flights take place in the lower stratosphere, especially in mid and high latitudes from late autumn to early spring. The emissions from these flights can affect the ozone levels in the lower stratosphere. The subsonic aircraft emit NO_x in the lower stratosphere during the seasons when the lower stratospheric ozone is most vulnerable to catalytic destruction. During summer, the current subsonic aircraft do not usually fly in the stratosphere. However, as the aircraft fly higher for fuel efficiency and operational reasons, a larger fraction of the flights will be in the stratosphere and possibly even during summer. Emissions higher up in the troposphere may also be transported into the stratosphere. Hence, subsonic aircraft are of concern.

The principal contributors to the session on Stratospheric [illegible]

Mack McFarland:	Session Chair
Dean Peterson:	Rapporteur
Roderic Jones:	A tutorial
David Fahey:	Where are we in understanding [illegible]
Richard Rood:	Special role of stratosphere troposphere [illegible]
Richard Stolarski:	The stratosphere in the year 2050: Can we predict it?
Tore Knobloch:	Provocateur

D. Tropospheric Ozone: The Newer Issue

Background

In most of the troposphere, unlike the stratosphere, molecular oxygen cannot be photodissociated by solar radiation to generate ozone. Radiation capable of dissociating oxygen is filtered out in the stratosphere before it reaches the troposphere. So, where does tropospheric ozone come from? For a long time it was believed that the stratosphere was the only source of tropospheric ozone. During the past two decades, it has become clear that a large fraction of the lower tropospheric ozone is photochemically produced, *in situ,* and this chemical production can be (and is) influenced by human activity. A significant fraction of the ozone, no doubt, comes from the stratosphere, but it may not be the dominant source for the entire troposphere. However, the contributions of photochemical ozone production to the upper troposphere, where subsonic aircraft deposit most of their exhaust, are uncertain.

There is ample evidence for photochemical ozone production in the troposphere. For example, urban air pollution, characterised by high ozone levels, is common all over the industrialised and developing countries. Historic records of surface ozone in the northern hemisphere clearly show an increase in the background levels since industrialisation. The photochemical production mechanism is reasonably well understood, even though quantitative calculations are not very accurate because of a lack of other information.

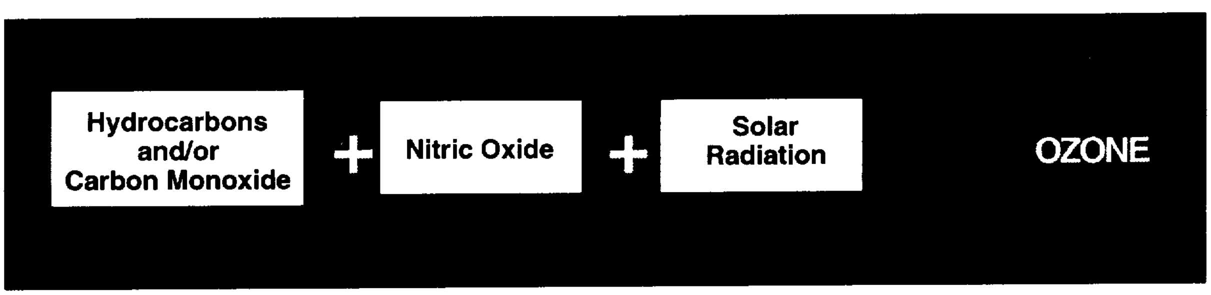

Figure II-D-1. Tropospheric Ozone Production

The key ingredients for the photochemical production of ozone in the troposphere are hydrocarbons or CO, nitrogen oxides and near-UV and visible light. Hydrocarbons and CO act as fuels that are slowly oxidised in the atmosphere with the byproduct being ozone. Calculation of the ozone production rates requires, among other things, complete information on the sources (amount and nature) of hydrocarbons and the amounts of nitrogen oxides. These sources are hard to quantify because both hydrocarbons and nitrogen oxides have natural and anthropogenic components.

To define the concentration of ozone in a given region, which is controlled by a balance between production and removal, the rate of removal from that region of the troposphere has to be known quantitatively. The removal of ozone from a given region is controlled by not

only the chemical losses but also by the dynamics of the air motion. Air motions in the troposphere are more complex than in the stratosphere and the time scales for chemical removal and physical transport are comparable and, hence, inseparable. Thus, the ozone removal rate is another factor that needs to be better defined to fully elucidate the effects of aircraft emissions.

The major sources of hydrocarbons are vegetation, biological activity, and anthropogenic emissions. One finding of significance from global measurements is that hydrocarbons are ubiquitous. The less reactive ones, such as methane, are everywhere in the troposphere. The more reactive ones are usually confined to the regions where they are emitted. The current emissions of hydrocarbons and carbon monoxide by aircraft under cruise conditions are known to be small, and the same is expected in the future. Therefore, the contribution of aircraft to the level of hydrocarbons and CO in the troposphere on a global scale is negligible. So, the main contribution of aircraft that can change ozone is emission of nitrogen oxides.

Tropospheric ozone has a vastly different effect in the Earth system than its stratospheric counterpart. Stratospheric ozone is desirable because it is a UV shield. Many of the effects of enhanced tropospheric ozone are detrimental to the biosphere. Unlike in the stratosphere, ozone in the troposphere near the surface comes in contact with the biosphere. Since ozone is an oxidant and a toxic substance, its presence is not generally desirable. But, small levels of ozone are actually beneficial in the troposphere since ozone generates various cleansing reactive species, such as the hydroxyl radical (OH), without which most emissions into the troposphere would accumulate. However, high levels of surface ozone lead to problems, mostly in terms of health effects and decreases in crop production. Therefore, an increase in tropospheric ozone levels much above the current background values is not desirable.

Ozone, in addition to acting as a UV filter, is also a greenhouse gas. Its effectiveness as a greenhouse gas is largest in the upper troposphere and the lower stratosphere. Ozone is different from all other greenhouse gases in two respects: (1) it is much shorter lived than the other greenhouse gases and, consequently, it is not well mixed in the troposphere, and (2) it is not directly emitted into the atmosphere by anthropogenic activity but, rather, is produced in the atmosphere by anthropogenic emissions. This factor has made it difficult to quantify the consequences of many emissions, for example the nitrogen oxides, which are often the limiting reagents in producing ozone.

Ozone production in the upper troposphere requires the presence of hydrocarbons or CO and nitrogen oxides. Since most of the anthropogenic activities that emit these species take place close to the surface, such activities may not greatly influence the upper troposphere. Surface emitted species have to be transported into the upper troposphere for them to be effective. Compared to all other anthropogenic activities, the aircraft-source is unique: it emits reactive species *directly* into the upper troposphere.

Because of the above reasons, there is a considerable concern in recent years regarding effects of aircraft on changes in ozone levels. This session addressed one part of the concern: to what extent do aircraft emissions change tropospheric ozone?

Key Points

The key points and uncertainties that emerged from the ensemble of talks and subsequent discussions regarding the effects of aircraft on the tropospheric ozone are given below. They are not an assessment of the problem and are not presented in any order of priority or concern.

1. *Ozone and particles can alter the composition of the troposphere.* Ozone will impact the composition of the troposphere via its reactions and the reactions of its photochemical products. Changes in the particle concentrations can also alter the composition of the troposphere. Ozone controls the rates of oxidation of various tropospheric species. Changes in ozone and particle levels have the potential to alter the oxidising capacity of the troposphere. The radiative effects and the influence on composition are individually important; but they can also act synergestically.

2. *Ozone in the upper troposphere has both natural and anthropogenic sources.* A part of the upper tropospheric ozone is transported from the stratosphere and a part is photochemically produced from natural and human influenced sources. Increases in surface levels of ozone subsequent to industrialisation have been recorded and are clear indicators of its photochemical production in the lower troposphere. A quantitative accounting of the contribution of the photochemical production of O_3 to mid-and upper troposphere cannot be made reliably. However, it may be a significant source. Some investigators estimate the photochemical source to be as large as transport from the stratosphere, especially during the summer months. Other investigators contend that the stratospheric transport is the major source of ozone in the upper troposphere. This is a highly important, but unresolved, issue which requires further research.

3. *Nitrogen oxides from the aircraft are agents for ozone changes in the upper troposphere.* Nitrogen oxides from the aircraft are the primary emissions that can induce a change in tropospheric ozone via photochemical production. Often, nitrogen oxides can be the limiting agents in ozone production and, hence, aircraft emissions can have a substantial effect. The emission from the aircraft can be accounted for reasonably well and the fractional contribution of the aircraft to the upper tropospheric NO_x (defined as the sum of NO and NO_2) has been estimated. The fractional contributions differ somewhat from model to model. These estimates are uncertain because of the uncertainties in the rates of natural emissions and transport into and out of this region of the troposphere. In particular, the production due to lightning and exchange between the lower and upper troposphere are very uncertain.

4. *Emission of nitrogen oxides by aircraft in the troposphere is expected to increase ozone.* The effect of increases in NO_x on ozone amounts is not linear and, at high concentrations of NO_x, increases in NO_x can even decrease the ozone abundance. Therefore, it is critical to know the background levels of NO_x into which the emissions occur. Even though the

background levels of NO_x in the upper troposphere are uncertain, they are known to be small enough that the NO_x emitted by aircraft into the current upper troposphere is expected to increase the level of ozone in this region. However, because the quantitative relationship between the extent of ozone production and NO_x concentration is highly non-linear, quantification of the increase in ozone per unit emission of NO_x is uncertain. Quantification of this increase via improvements in models and field measurements is one of the key challenges to research in this area.

5. *Enhancements of NO_x and total reactive nitrogen (NO_y, the sum of NO_x and N_2O_5, HNO_3, and other nitrates) in the upper troposphere on a hemispherical scale due to aircraft is unresolved.* Direct measurements of the concentrations of nitrogen oxides and their end products cannot reveal if aircraft have increased the levels of nitrogen oxides in the upper troposphere on a hemisphere scale. However, there is evidence for enhancements in NO_x levels in the flight corridors of the North Atlantic. Some measurements suggest that the contribution of aviation to NO_x in the upper troposphere at mid to high northern latitudes (30 to 60°N) is significant. Not enough measurements have been made in the critical areas of the globe to ascertain the global contribution of aviation. Rapid chemical conversion, deposition, and transport make such quantification difficult.

6. *Current observations do not reveal if aircraft have changed tropospheric ozone.* There is no clear signature for aircraft induced O_3 changes in the upper troposphere in the recorded ozone measurements. It is also not clear if one should be "visible" for the level of current activity because ozone in the upper troposphere is highly variable and the expected changes due to aircraft are small. A further complication is that the concentration of O_3 in the lower stratosphere is decreasing due to anthropogenic emissions of halogen containing compounds. The decrease in this source of tropospheric ozone makes it difficult to identify a trend due to aircraft.

7. *We cannot up to now quantitatively estimate the effects of growing aircraft activity on tropospheric ozone.* Even though the photochemical production of ozone can be calculated if the source strengths are known, we cannot currently quantify the aircraft-induced changes in ozone concentrations because: (a) we cannot accurately quantify the ozone transport and removal processes and (b) the fraction of nitrogen oxides that comes from aircraft is ill-defined. The chemical ozone removal processes are believed to be better known than the production processes. Vertical transport is more poorly known than the chemical removal processes. Yet, many scientists suggest that ozone will likely increase due to aircraft emissions. Until tropospheric transport and the nitrogen oxide budget are better defined, it will be difficult to accurately calculate the contribution of aircraft to ozone levels.

8. *Aircraft do not significantly enhance acid precipitation.* It is clear that the contribution of aircraft to acidic precipitation on a global and region scale is very small, a few percent, as long as the fuel consumption due to aircraft is a small fraction of that in energy production and ground transportation.

The principal contributors to the session on Tropospheric Ozone

Anne Thompson:	Session Chair
Hans Schlager:	Rapporteur
Guy Brasseur:	A tutorial
Frank Arnold:	Aircraft contribution to tropospheric NO_x and NO_y
Jennifer Logan:	How well can we calculate tropospheric O_3 and aircraft contribution to this abundance?
N. Sundararaman:	Provocateur

E. Greenhouse Gases and Climate: The Emerging Issue

Background

The presence of gases in the atmosphere that can absorb infrared radiation emitted by the Earth's surface and the atmosphere prevents the Earth from being a frozen planet. This is the greenhouse effect, a phenomenon which has been known since the 1880's. The presence of the most abundant greenhouse gases, water and carbon dioxide, is essential for the survival of life on Earth. However, increases in greenhouse gases can alter the climate from the current state to another that is different (most likely warmer) and likely will alter human lifestyle. Ice core data clearly show changes in temperature corresponding to changes in the abundances of greenhouse gases. Such correlations alone are not proof of greenhouse gas induced warming, but they are consistent with our understanding of these processes. It has also been clear through observations that human activity can produce greenhouse gases and alter the composition of the atmosphere. Therefore, it is logical to expect climate change from increases in anthropogenic emissions of greenhouse gases.

Climate change is expected to alter the sea level, change precipitation patterns, and induce other changes that greatly affect the social and economic state of Earth's population. Biological systems may not be able to cope with the rapidity of the changes. That is the main concern about human induced climate change.

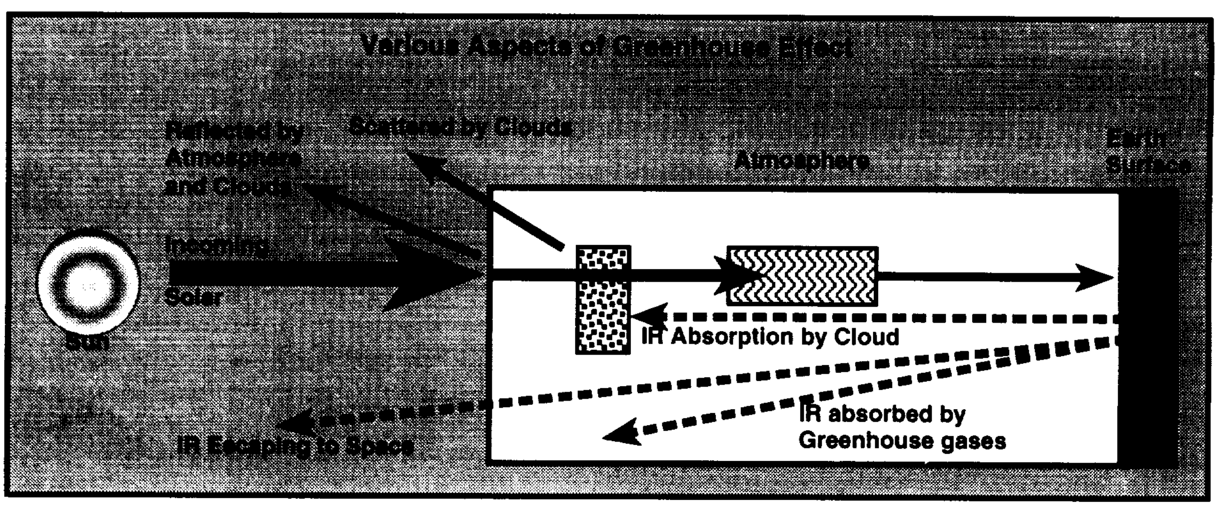

Figure II-E-1. Schematic Diagram of the Greenhouse Effect

The solar radiation, most of which is concentrated in the visible part of the spectrum, enters the atmosphere. Part of this radiation is reflected or scattered back to space by the atmosphere, particulate matter, and clouds. Part of the radiation is absorbed by atmospheric constituents and heats the region where the absorption takes place. The remainder of the radiation reaches the surface, where it is absorbed or scattered back. The energy absorbed by

the atmosphere and the surface is radiated as infrared radiation; this is usually referred to as the "outgoing infrared." The amount of solar radiation absorbed and the amount of infrared radiation leaving the Earth/atmosphere system must balance over long time periods and reach an equilibirum. Greenhouse gases, clouds and particles trap part of the energy at and near the Earth's surface. If the outgoing infrared radiation is inhibited because of increased absorption by added greenhouse gases, the system reaches a new equilibrium with a warmer surface than the one without the added absorbers. Thus, addition of greenhouse gases will increase the temperature of the Earth's surface and the atmosphere close to the surface. It may also alter the temperature structure of the atmosphere. The non-equilibrium, instantaneous change in the amount of radiation leaving at the top of the troposphere due to an instantaneous change in the concentration of a greenhouse gas is called the radiative forcing. Radiative forcing is often used as a measure of the effectiveness of a gas to act as a greenhouse gas.

The most important greenhouse gas is water vapour, which is natural in origin and whose concentration in the atmosphere is controlled by the hydrological cycle. Carbon dioxide is the next most important absorber. The increase in the amount of infrared absorption is not linear with increase in the abundances of water vapour and carbon dioxide because much of the absorbable radiation is already absorbed in the present atmosphere. In addition to the natural greenhouse gas effect of ~150 Wm^{-2} of infrared radiation absorbed by water vapour and CO_2, the increases in greenhouse gases since industrialisation due primarily to human activity currently absorb approximately 2.5 W m^{-2}. This is currently a significant perturbation, and is expected to increase strongly during the next century. Although CO_2 is the most important anthropogenic greenhouse gas, the contributions to the radiative forcing by methane, CFCs, and nitrous oxide since industrialisation is calculated to be equal to that of industrial CO_2.

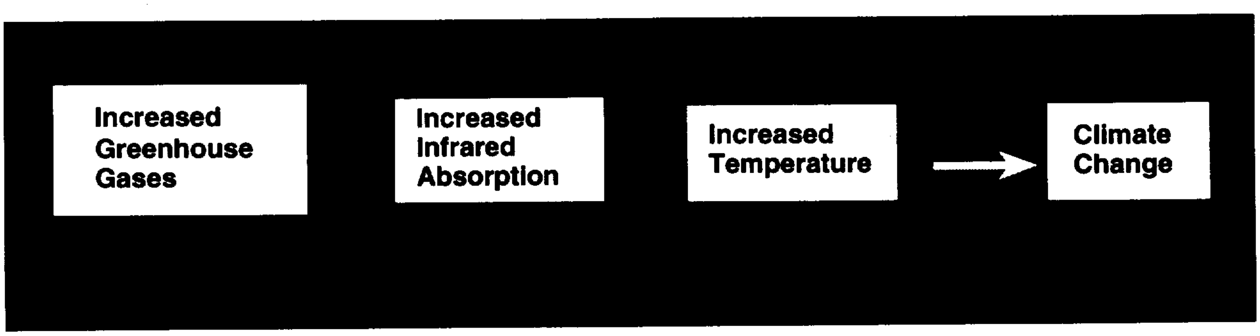

Figure II-E-2. The Global Warming Issue

Even though the amount of infrared radiation absorbed by the greenhouse gases can be calculated quite accurately, translating the increase in absorbed energy to increases in temperatures is difficult. The prediction of climate change is even more uncertain. This is because the response of the Earth system to an increase in energy absorbed is very complex, affected by inertia of large heat sinks such as the oceans, and feedbacks. The response function, i.e., change in surface temperature per unit flux of absorbed energy is not well

defined, but is believed to be between 1.5 to 4.5 K for doubling of CO_2. There is evidence to suggest that the global mean surface air temperature has warmed by 0.3 to 0.6 K since the late 19th century and that this increase is most likely due to anthropogenic emissions of greenhouse gases. Predicting regional climate change (e.g., precipitation) from the temperature changes or radiative forcings is even more uncertain and complex. This is because of a large number of feedback mechanisms that are operative and the non-uniformity in the changes in the radiative forcing. Further, the climate system is chaotic and, thus, makes changes induced by small forcings more difficult to detect or predict. Thus, even though there is a qualitative feel for the changes in climate due to changes in the concentrations of greenhouse gases, quantitative or even a semi-quantitative estimate of the climate change is very difficult and uncertain. All such predictions are based on very complex models of the Earth system that are incomplete.

Atmospheric observations over the past decades have clearly shown that human activity can alter the atmospheric concentrations of greenhouse gases such as CO_2, CH_4, N_2O, and CFCs. The levels of ozone in the atmosphere have also been observed to change, at least partly due to human activities. A decrease in the stratospheric ozone level enhances transmission of biologically damaging UV radiation to the surface. An increase in the tropospheric ozone, where it acts very effectively as a greenhouse gas, increases the absorption of the outgoing infrared radiation. In contrast to the greenhouse gases, particulates in the atmosphere can decrease the incoming solar radiation directly or via enhanced formation of reflective clouds. Aircraft can potentially alter the atmospheric abundances of CO_2, H_2O, O_3, and particulates. They emit them in the parts of the atmosphere where such emissions can disproportionately alter the radiation budget. Therefore, the consequences of aircraft emissions on the climate of the Earth is of concern.

Key Points

The key points and uncertainties that emerged from the ensemble of talks and subsequent discussions regarding the effects of aircraft on greenhouse gases and climate are given below. They are not an assessment of the problem and are not presented in any order of priority or concern.

1. *Aircraft emissions can alter the atmospheric concentrations of greenhouse gases and particulates.* Combustion of fossil fuel in aircraft engines produce CO_2 and H_2O, which are greenhouse gases. In addition, the emissions of nitrogen oxides lead to the production of ozone in the troposphere. Output of particulates and their precursors are also important. Quantification of these emissions and their subsequent atmospheric transformations will enable us to compare the climate effects of aircraft with those from other anthropogenic activities.

2. *Perturbations caused by aircraft emissions are also caused by other anthropogenic activities.* The emissions of CO_2, water vapour, nitrogen oxides (that lead to tropospheric ozone production), particulate matter and the precursors of particulates are not unique to aircraft. Other activities involving fossil fuel and biomass combustion also produce such emissions. Therefore, aircraft emissions and their effects may be compared with those

from other anthropogenic activities. However, the location of the emissions by aircraft is different from all other anthropogenic activities and has to be taken into account.

3. *Consequences of H_2O and NO_x emissions from aircraft may be disproportionately larger than their fractional contribution to the overall atmospheric abundance.* CO_2 emitted by aircraft is long lived and mixes with the large background of this compound in the atmosphere. Therefore, it has the same effect as CO_2 derived from other combustion. In contrast, water vapour from aircraft is injected directly into the water poor regions in the upper troposphere and lower stratosphere. Water vapour can absorb IR radiation, lead to clouds, alter heterogeneous reaction rates, and change the concentrations of free radicals. Therefore, depending on the location, its emission may have very significant effects. Similarly, nitrogen oxides which lead to production of ozone, a radiative gas, are also injected into regions of low background abundances. Therefore, small injections of H_2O and NO_x may have disproportionately large effects.

4. *Radiative forcing, though imperfect, may be a tangible measure of the climate effects of aircraft emissions.* The radiative forcing from the aircraft effluents may be compared to the radiative forcings from other anthropogenic activities. Because of the long atmospheric lifetime of CO_2, the radiative forcing due to aircraft emitted CO_2 can be compared directly with that due to other anthropogenically produced CO_2. Similar comparisons for tropospheric ozone may not be as viable because the response of the Earth system to different radiative forcings may not be the same, depending on the altitude of the perturbation.

5. *With the exception of CO_2, which is relatively long lived, the response of the atmosphere to regulations on aircraft emissions will be rapid.* Once the emissions of water vapour, nitrogen oxides, particulate matter, and precursors to particles cease, all the emissions and their atmospheric products, with the exception of CO_2, are removed from the atmosphere within a few years or sooner. The time scale for removal from the troposphere is shorter while that from the stratosphere could be a few years. Thus, the response of the atmosphere to cessation of emissions is expected to be prompt. However, the effects due to CO_2 will persist.

6. *Direct forcing by long-lived greenhouse gases from aircraft is of the order of 3%, or less, of that due to all other industrial activities.* The direct radiative forcing due to greenhouse gases emitted CO_2 and H_2O vapour by current air traffic is estimated to add up to 0.05 Wm^{-2} compared with 2 to 3 Wm^{-2} due to all industrial greenhouse gas emissions (i.e., the sum of CO_2, CH_4, CFCs, and N_2O). The total forcings is uncertain because the above estimates do not include indirect effects such as O_3 production and the consequences of aircraft emissions on particle formation in the atmosphere. The effects due to CO_2 are cumulative, on decadal time scale, and the aircraft contribution is likely to grow. Therefore, the impact of aircraft will be larger in the future.

7. *The forcing by aircraft induced ozone changes is a non-negligible fraction (up to 10%) of that due to tropospheric ozone produced by anthropogenic activities.* In terms of the production of ozone, aircraft emissions are expected to be disproportionately more effective because of their

location. Aircraft production of nitrogen oxides is only a few percent of the total anthropogenic NO_x emissions in the troposphere. However, aircraft emissions are expected to contribute more to the radiative forcing by ozone in the troposphere because the emissions are in the upper troposphere. In the upper troposphere, the radiative forcing by unit amount of ozone is larger than in the lower troposphere.

8. *The changes in the radiative balance due to changes in the stratosphere is very dependent on altitude and latitude.* The magnitude and vertical structure of temperature change due to alterations in the ozone abundance critically depends on the location of the ozone change. A small change in the lower stratospheric or upper tropospheric ozone can cause relatively large changes in temperature. The effect of ozone is strongest over warm Earth surface, i.e., tropics, and smallest over cold parts, i.e., the polar regions. The NO_x emissions by subsonic aircraft may enhance ozone in the upper troposphere. Subsonic aircraft emissions in the lower stratosphere may also alter ozone. Thus, the climate impact of subsonic aircraft may be important, depending on the location of emissions and on whether they are transported poleward or equatorward. On the other hand, supersonic aircraft emissions at the higher altitudes contribute to ozone destruction but its climate consequence is believed to be smaller. However, ozone loss at higher altitudes will affect ozone levels further down in the stratosphere.

9. *The role of clouds is a major uncertainty in evaluating the effects of greenhouse gases.* The effects of clouds depend on their altitude, water content, thickness and cloud particle size. The impact of clouds on climate is known to be large; yet it is poorly understood. The extent to which the hydrological cycles can be altered due to changes in greenhouse gas abundances and how the changes in hydrological cycle affect cloud properties and coverage are very uncertain. Therefore, the complete impact of greenhouse gas changes cannot be evaluated well at this time.

The principal contributors to the session on Greenhouse Gases and Climate

Ivar Isaksen:	Session Chair
Robert Sausen:	Rapporteur
Robert Cess:	A tutorial
Jos Lelieveld:	The influence of chemistry on greenhouse gases
Marvin Geller:	Climate consequences of ozone changes in the stratosphere
Michael Prather:	The relationship of radiative forcing to climate
Jan Westerberg:	Provocateur

F. Aerosols, Chemistry, and Climate: A New Focus

Background

Aerosol is a suspension of condensed matter (liquid or solid) in a gaseous medium. Such condensed matter exists naturally in the atmosphere and has many important consequences. Aerosols are also often byproducts of industrial activity. Aerosols alter visibility, provide sites for chemical reactions many of which do not occur in the gas phase, cause health problems when inhaled, provide a site for nucleation of ice and water droplets, and provide means to remove many constituents from the atmosphere. Examples of the effects of aerosols have been known for a long time. However, the global nature of their effect on radiation and chemical composition has only recently been recognised.

Aerosols directly interact with both incoming solar and outgoing infrared radiation and, thus, alter the radiative balance in the atmosphere. The ability of aerosols to alter radiative balance and, hence, temperature has been amply demonstrated by volcanic eruptions and the subsequent temperature changes. The role of anthropogenic aerosol in altering the climate of the Earth has received much attention recently. This followed the recognition that sulphate aerosols from combustion of sulphur-containing fuels and carbonaceous aerosols from biomass burning can substantially alter the radiative balance. Therefore, the impact of aircraft has to be judged relative to those from natural phenomena and other activities from industry to agriculture.

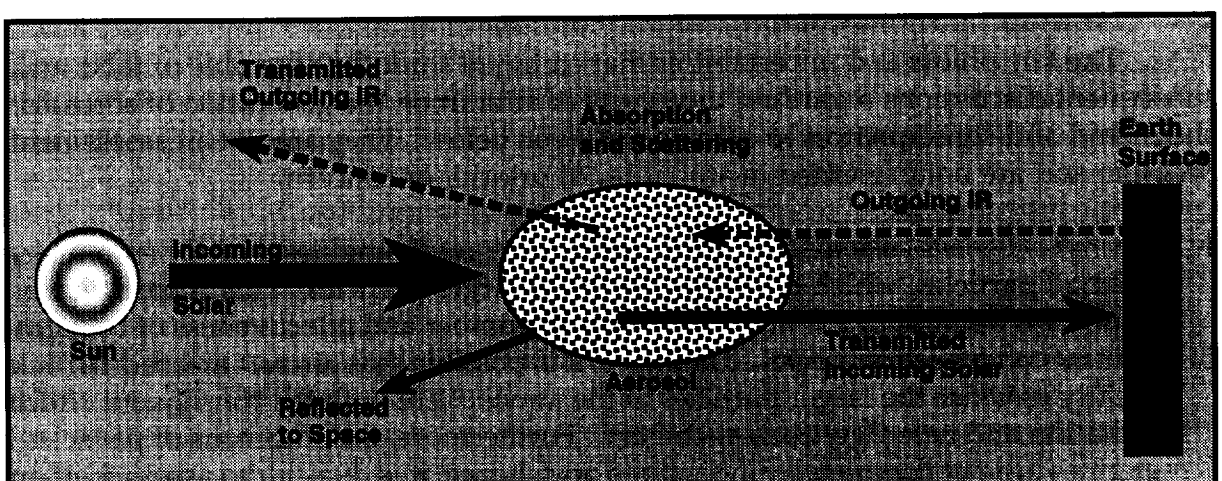

Figure II-F-1. Aerosols and the Radiation Budget

Aerosols interact directly with radiation by (a) scattering or absorbing incoming solar radiation and (b) scattering or absorbing and re-emitting outgoing infrared radiation. Soot, in general, absorbs incoming solar radiation while for most other aerosols scattering is more important. Aerosols also lead to creation of new absorbers and scatterers by acting as

condensation nuclei for clouds. They indirectly alter the radiative properties of clouds by changing their size distribution (i.e., the number of particles per unit water content) in the atmosphere and, hence, change the radiative balance. Clouds absorb infrared radiation and, hence, their increase leads to warming. This is particularly efficient for high cold clouds (e.g., cirrus) . For low clouds, the scattering of solar radiation is more important and leads to cooling. In addition, heterogeneous chemistry on aerosols may lead to composition changes that alter the abundance of long-lived greenhouse gases. Thus, aerosols play a very major role, directly and indirectly, in altering the radiative balance of the atmosphere and, hence, climate.

A reduction in the incoming solar radiation reaching the surface leads to a cooling of the atmosphere and the surface. Currently, it is suspected that the anthropogenic sulphate aerosols derived from combustion cool the surface and, thus, regionally mask to some extent the heating due to increased CO_2 and other greenhouse gases. The magnitude of the cooling is currently uncertain and the aerosol effect is regional, while that of the long-lived greenhouse gases is global. Further, quantification of the contributions of the aerosols has been hampered by a lack of knowledge on the indirect effects, amplification due to water vapour changes, and inhomogeneity of the tropospheric sulphate aerosols.

It is now known that aircraft, subsonic and supersonic, emit new particles, precursors to new particles, and ingredients needed to grow and sustain existing particles. In the upper troposphere, aerosols can directly interact, or create particles that can interact, with radiation and have profound climate effects. This is also the region where subsonic aircraft fly. That is another reason for the concern that aircraft may alter Earth's climate.

Key Points

The key points and uncertainties that emerged from the ensemble of talks and subsequent discussions regarding the effects of aircraft on the generation of aerosols, their chemistry, and consequences to climate are given below. They are not an assessment of the problem and are not presented in any order of priority or concern.

1. *Aircraft emissions enhance atmospheric aerosols.* Aircraft engines directly emit a large number of small particles, which can act as nuclei for larger particles. This is particularly important because of the high variability in number and effectiveness of background natural condensation nuclei. Therefore, it is possible that aircraft emitted particles may greatly enhance the larger particles in the atmosphere with the consequent effects on radiation and heterogeneous chemistry. Furthermore, the emissions of particles by aircraft engines are not completely understood and, hence, it is difficult to assess their emission strength and variability from engine to engine and in new engine designs. In addition to the particles, aircraft emit sulphur and nitrogen compounds and water vapour. Oxidation of sulphur compounds produces sulphuric acid. The presence of sulphuric acid and water vapour can enhance the surface area of existing particles or create new particles. The formation of nitric acid from aircraft exhaust can lead to formation of Type I polar stratospheric clouds (PSCs), which are made up of HNO_3, H_2O, and possible H_2SO_4, if the emissions are in the polar stratosphere and, possibly, in the cold humid regions of the upper troposphere.

2. *The direct radiative effect of aircraft generated aerosols are likely to be very small.* The atmosphere has a large amount of aerosol from various natural and anthropogenic emissions. The increase in the number and the optical depth of aerosols from aircraft, on a global scale, compared to the background is too small to significantly increase the direct radiative forcing of the atmosphere.

3. *Increases in contrails/cirrus cloud coverage may lead to a net warming.* The aircraft generated or induced particles and the emitted water vapour may lead to enhanced contrails/cirrus cloud formation. The enhanced contrails/cirrus clouds can decrease the incoming solar radiation and alter the outgoing infrared radiation. It appears that, in balance, the absorption outweighs scattering and, thus, cirrus clouds and contrails in the upper troposphere lead to a net warming.

4. *Contrail-Cirrus cloud connection is uncertain.* It is possible that the evaporation of the contrail leaves a set of particles that are better ice nuclei than the background particles. If true, the formation of cirrus will be enhanced due to the availability of ice nuclei. In such a case, the radiative forcing by the aircraft induced cirrus could be substantial.

5. *The effect of aircraft generated particles on cirrus is currently too uncertain for quantifying the climate forcing by aircraft emissions.* The indirect enhancement of cirrus clouds by aerosols may be the most likely way aircraft can significantly alter climate. However, this indirect effect is very uncertain because (a) the role of clouds in the Earth's radiation budget is not well quantified and (b) the extent to which aircraft generated aerosol alter the clouds is not understood. The aircraft generated particles may also alter the optical properties of natural clouds at lower altitudes. If this alteration is significant, the effect of aircraft on climate may be very substantial. Some scientists, for example, suggest that aircraft generated particles may lead to a 1% larger cloud cover with a consequent increase in radiative forcing of 0.25 Wm^{-2}. This is ~15% of the industrial forcing by CO_2 and will be much larger than the contribution due to CO_2 produced by aircraft. However, there is little evidence to suggest such large changes. This is a priority topic for research and better estimates are likely in the future.

6. *Aerosols can alter the composition of the atmosphere and thus alter climate.* The aircraft generated aerosols themselves, or the subsequently formed particles, will provide sites for heterogeneous reactions. In the stratosphere, the heterogeneous reactions may activate chlorine and lead to changes in ozone abundance. In the troposphere, the heterogeneous reactions may alter the concentrations of free radicals and, consequently, those of some greenhouse gases. This sequence of events is neither proven by observations nor quantified by calculations. The possibility that ice particles in the upper troposphere provide sites for heterogeneous reactions has not yet been investigated. It is currently believed the change in radiative forcing via alterations in the concentrations of greenhouse gases other than ozone is negligibly small. Changes in the vertical distribution of ozone in the upper troposphere/lower stratosphere can have significant consequences. (see previous sections.)

7. *Direct radiative effect of soot from aircraft exhaust is unlikely to be significant.* Soot, unlike other aerosol can absorb incoming solar radiation and lead to a heating of the region directly. The extent to which aircraft would increase soot in the upper troposphere/lower stratosphere is uncertain, but is estimated to be small.

8. *Understanding clouds, and particularly cirrus clouds, may be important for quantifying the climate effects of aircraft.* Because the direct radiative forcings by the aircraft generated aerosols and emitted greenhouse gases are probably small, only through alterations of cloud properties and coverage can aircraft substantially alter climate. However, our understanding of these processes is currently too uncertain to quantify their contribution and even estimate if they are significant. Further improvements in our knowledge of cirrus clouds are expected in the near future.

The principal contributors to the session on Aerosols, Chemistry and Climate

Hartmut Grassl:	Session Chair
Estelle Condon:	Rapporteur
Joyce Penner:	A tutorial
O. Brian Toon:	Cirrus clouds: their connection to climate and aircraft
Bernd Kaercher:	How do aerosols/clouds change composition and radiation
Martin Wright:	Provocateur

G. Overall Effects of Aviation on The Atmosphere

Background

The impacts of aviation on the environment are numerous and vary in extent and coverage. They range from local phenomena such as airport noise and local pollution to regional scale effects to global scale impacts. The subsonic aircraft emit in the upper troposphere and lower stratosphere, regions which can be altered by small emissions. The proposed HSCTs would emit at higher altitudes in the stratosphere where ozone abundances are susceptible to aircraft emissions. Therefore, aircraft are expected to affect the atmosphere and Earth's climate. In this symposium, only the following global scale impacts are addressed: (a) the depletion of stratospheric ozone, (b) the change in the abundance of tropospheric ozone, (c) alterations of the radiative balance of Earth via increases in greenhouse gases (primarily CO_2 and O_3), and (d) alterations of the radiative balance of Earth via changes in aerosols and particulate matter due to aircraft.

It is clear from the discussions at the symposium that aircraft can have many diverse impacts and they are all interconnected in some ways. The production of ozone in the troposphere is not only a concern because of the changes in the composition of the troposphere but also because of climate consequences. Stratospheric ozone depletion impacts not only the UV levels that reach the Earth's surface but also the climate because it changes the vertical profile and abundance of this greenhouse gas. Yet, some times, these impacts can be artificially separated to place a specific impact in perspective. For example, the level of ozone depletion by aircraft can be compared to the depletion induced by the emissions of CFCs, even though the regions where such depletion take place are not exactly the same. In addition, the impacts of two effluents from the aircraft may affect the climate or ozone in opposing or synergistic ways. Then the overall effect of aviation may be different from considering the specific impacts separately. Furthermore, even if the impacts are of opposite direction, it does not mean that they cancel! For example, they may affect different regions of the atmosphere. Therefore, the assessment of the overall impact is not a simple task of arithmetical manipulations of the effects, but rather an effort to place the possible effects on scales that will enable scientists, technologists, and the decision makers to compare the effects with those from other anthropogenic activities.

In terms of comparisons, the stratospheric ozone depletion is best compared with the ozone depletion attributed to the emission of CFCs. The changes in the radiative forcing attributed to aviation induced changes in greenhouse gases can be compared with the radiative forcing due to CO_2 emissions from total fossil fuel usage or that from the transportation sector. The changes in particle loading due to sulphur and soot emissions may be compared with the changes induced by major volcanic eruptions or biomass burning. Such simple comparisons may or may not be feasible. Equivalent radiative forcings occurring in different atmospheric locations may not have comparable climate impact. This is an area of current climate research.

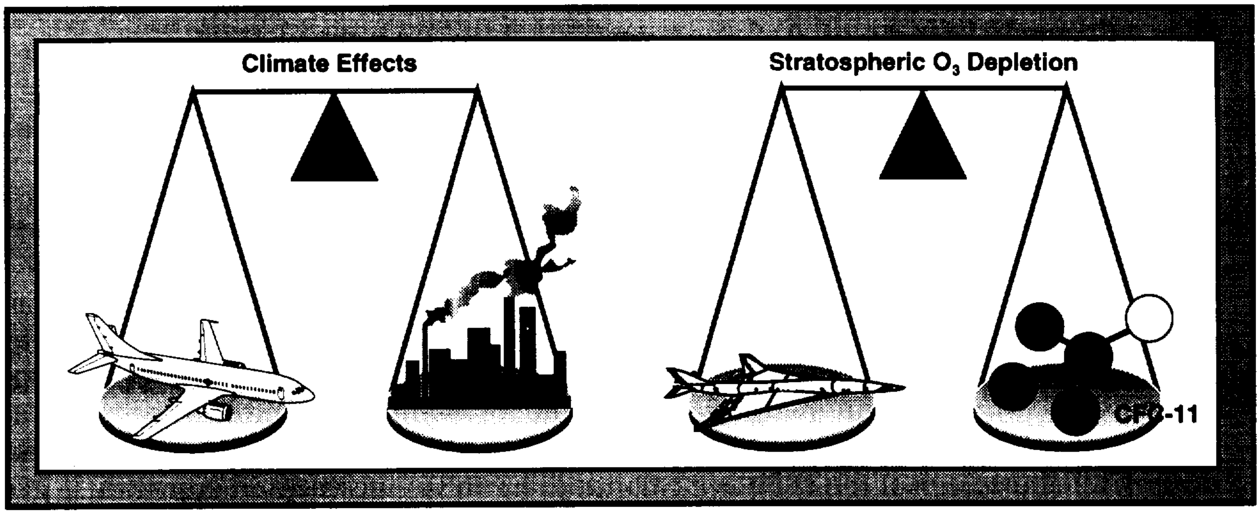

Figure II-G-1. A Study of Risks: Comparison of one environmental issue with another

The impact of aircraft has to be assessed for today's atmosphere as well as the one in the future. The future atmosphere will be changing due to both natural variations and anthropogenic impacts, as described earlier. For example, the impact of HSCT on stratospheric ozone depletion has to be evaluated in an atmosphere where the chlorine loading will be decreasing throughout the next century and natural perturbations like volcanic eruptions are unpredictable. Similarly, the climate impact of the atmosphere has to be assessed on an ever-changing abundance of CO_2 and possibly an atmosphere with changing sulphate aerosols. The changing "reference frame" makes the assessments more difficult.

Based on all the discussions of the individual effects, it is clear that the effects of aircraft on the atmosphere are highly diverse and variable and may be significant enough to be of concern. This session addressed the overall effects of aircraft on the atmosphere.

Key Points

The key points and uncertainties and a few questions that emerged from the ensemble of talks and subsequent discussions regarding the overall effects of aircraft on the atmosphere are given below. They are not an assessment of the problem and are not presented in any order of priority or concern.

1. *The level of scientific understanding of different effects of aviation is highly varied.* Our understanding of the stratospheric ozone depletion is robust enough to attempt quantitative predictions, even though they are uncertain. Our understanding of tropospheric ozone changes due to subsonic aircraft is developing rapidly and may be amenable to estimations in the near future. The overall climate impact is less developed. Predictions of the effects of aviation on climate will be proportionately less certain. Other effects discussed in this symposium have levels of confidence in between these limits.

2. *The climate effects of aircraft emissions are potentially of major concern.* Aircraft emissions can potentially have many different effects on the atmosphere, i.e., ozone production and destruction, changes in the composition of greenhouse gases, alterations in the cloud properties and coverage. Of these, the effect of alterations to clouds due to aircraft and their consequent climate change has the potential to be large. However, the level of uncertainty is such that it can include negligible impact due to this effect.

3. *The direct climate effects of current aviation are likely much less than that of other anthropogenic emissions.* The total direct radiative forcing via changes in the greenhouse gases by aviation is roughly estimated to be ~ 0.05 Wm^{-2}, compared to the industrial CO_2 contribution of ~1.5 Wm^{-2} and the combined effect of industrial greenhouse gases of ~2 to 3 Wm^{-2}. Thus, the direct effects, though uncertain, are less than that due to current energy production or other modes of transportation. However, they may be significant in the future because of the likely growth in aviation.

4. *The indirect effects of aviation may have the potential to alter climate.* The direct effects of cirrus clouds are expected to be a net positive forcing. The radiative forcing due to changes in the cloud cover and alteration in cloud properties induced by aircraft is estimated to be positive. Some researchers estimate this effect could be very significant as compared to that due to industrial CO_2 emissions. This potentially large effect requires further research to find out the extent of the impact by contrails/cirrus clouds.

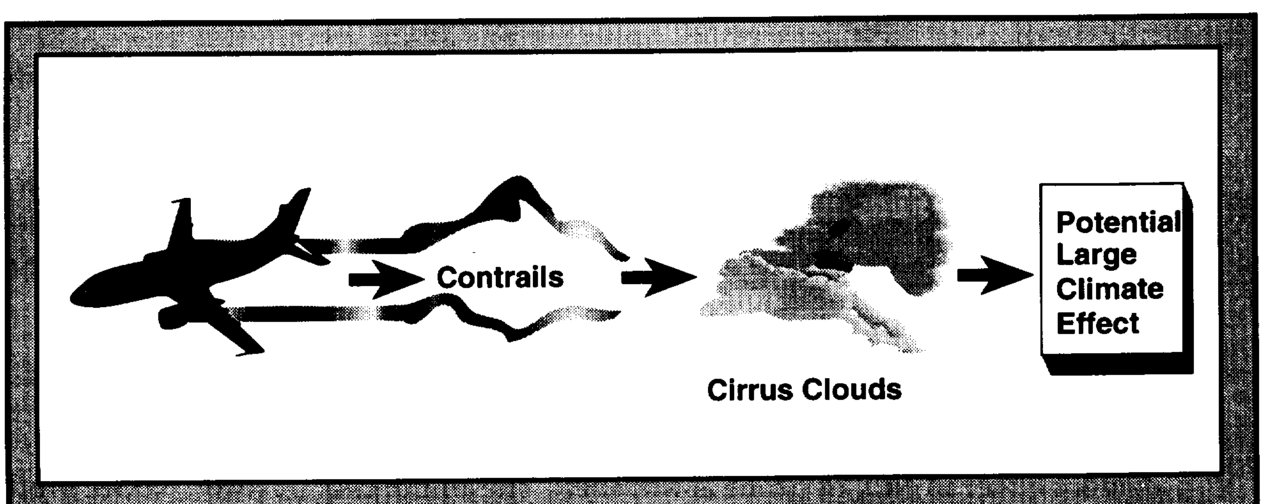

Figure II-G-2. Aircraft, Clouds, and Climate Change

5. *The primary effect of HSCT on the stratosphere is to change the ozone abundance via emitted NO_x.* The greatest global concern regarding HSCTs is the potential depletion of stratospheric ozone. The magnitude of this depletion is very uncertain but not as large as that due to the CFC emissions. Current models, which are known to be incomplete in their

representations of chemistry and dynamics, project steady state column ozone depletion of much less than 5%. Most models predict less than 1-2% depletion for a fleet of 500 HSCT aircraft with an emission index of 5 for nitrogen dioxide. For a larger emission index, the models predict larger depletions, but still less than 5% even for an emission index of 15.

6. *The impact of aircraft on the atmosphere will grow in the future.* Air traffic currently accounts for 5-6% of petroleum consumption and ~2.5% of fossil fuel consumption. Presently, the effects of aviation may be small compared to the natural variability or other anthropogenic activities. The fraction of fossil fuel used for aviation, as well as the total amounts, are expected to increase in the next decades. Because of growing passenger demand, aircraft emissions are likely to increase even when the fuel efficiency is increased. Therefore, the effects of aviation on climate and ozone changes are likely to increase in the next few decades and may be significant.

7. *The estimates of the effects of current aviation and the predictions of the future are uncertain.* Two-dimensional models have been used to predict the changes in ozone abundances in the troposphere and the stratosphere. However, they are incapable of dealing with feedbacks to the climate systems. The feedback and indirect effects can make the climate effects of aircraft emissions significant. Three-dimensional models are being developed and used for climate predictions. However, such models cannot yet assess the overall effect of aircraft quantitatively enough to enable comparison with other anthropogenic forcings. The models need to interactively couple radiation transfer, ozone changes, alterations in cloud coverage and properties, and effects of other emissions to fully understand the effect of aviation on the atmosphere. These requirements are being addressed.

8. *Nitrogen oxide emissions by aircraft are expected to enhance ozone levels in the upper troposphere.* The photochemical ozone production efficiency of nitrogen oxides, often the limiting agent in ozone production, varies with their concentrations as well as the atmospheric conditions and composition. In the relatively clean upper troposphere, emission of NO_x is expected to lead to a net ozone production. Therefore, one of the effects of aviation will be to increase the abundance of ozone in the upper troposphere. The extent of ozone increase is currently unclear.

9. *Changes in the nitrogen oxide abundances in the air traffic corridors have been observed.* Some field measurement campaigns have suggested increases in nitrogen oxide concentrations in the flight corridors. However, a regional or a global signature for air traffic is not evident either in NO_x or ozone abundance. The amounts of nitrogen oxides produced by natural phenomena, such as lightning, and transport from other regions are very uncertain. Therefore, the relative (i.e., to lightning and convective transport) contribution of aircraft induced nitrogen oxides to the upper troposphere cannot be calculated with certainty. However, the contribution is likely to be significant.

10. *What are the appropriate indices to measure climate impact of aviation?* The consequences of various aircraft effluents and the changes induced by them in the atmosphere are diverse and lead to different climate forcings. Some of these may appear to offset others as in the

case of radiative forcing with opposite signs. They may also impact different regions of the atmosphere. A single index to encapsulate the consequences of aircraft emissions on the atmosphere may not be feasible. One index for consideration is the radiative forcing, defined as the flux of radiation at the top of the tropopause that is changed, either via the attenuation of the incoming solar or absorption of the outgoing infrared radiation. The consequences of different impacts, expressed as radiative forcing, cannot necessarily be added to get the net impact, unless they are acting in the same region of the atmosphere and over the same time scales. Therefore, the radiative forcing may not be an acceptable index. Yet, currently we do not have any parameter, other than the radiative forcing, that better reflects the climate impacts of emissions. Further research is needed to answer this question.

11. *Can the impacts of supersonic and subsonic aircraft be compared?* One of the questions that requires answer in minimising any impact of aviation on the atmosphere is the consequence of substituting subsonic aircraft with supersonic aircraft. The primary effect of supersonic aircraft flying in the stratosphere is to deplete ozone. Thus this is a problem related to enhanced UV radiation. The climate impact of ozone depletion by the HSCT is unclear but must be evaluated. Enhancements of water vapour and, consequently, changes in climate, may be significant. Subsonic aircraft are expected to enhance greenhouse warming through increased tropospheric ozone and emissions of CO_2. A highly uncertain, but potentially large, effect of subsonic aircraft is through changes in high-level clouds with the consequent climate alterations. Thus, the impacts of subsonic and supersonic aircraft are different. It may be possible to evaluate the climate impact of the subsonic aircraft versus the supersonics in the future. However, further research is needed to make a meaningful evaluation.

The principal contributors to the session on Overall Effects of Aviation

Michael Oppenheimer:	Session Chair
Keith Ryan:	Rapporteur
Ulrich Schumann:	Summary of the overall effects and issues, and the importance of one factor over another
Michael Oppenheimer	Panel Discussion of the Overall Effects
Ulrich Schumann	
Mack McFarland	
Anne Thompson	
A. R. Ravishankara	
Albert Kaehn	
Georgios Amanatidis:	Provocateur

III. The Way Forward

A. Control of Emissions: Technology and Air Traffic Options

Background

Aircraft and engine technology developments, together with improved air traffic management and operational practices, are key elements in the control of the global emissions burden generated by aviation. Environmental charges or taxes could be used to encourage faster or more widespread implementation of these elements.

It was pointed out earlier (Section II-A) that the primary context in which manufacturers operate is one of competitive market forces. Therefore, their prime interest is to use available proven technology as much as possible and to optimise the overall system rather than to focus on single issues.

The aim of air traffic management is to ensure safe transfer of passengers and aircraft from point of departure to arrival whilst minimising operational costs to airlines and journey times for passengers. Within this concept, airlines adopt operational practices to maximise benefits to both their customers and themselves.

The summary and Key Points of the talks and discussions on control of emissions are as follows:

Technology

CO_2 and H_2O are the inevitable products of even the most complete combustion in an engine using aviation kerosene as its fuel. Although there may be some candidate alternative fuels, such as hydrogen and methane, none of them eliminate both CO_2 and H_2O emissions. Whilst hydrogen offers the potential for eliminating CO_2, it is at the expense of increased H_2O production. Currently, there are no real practical, economically viable, alternatives to kerosene as the commercial aviation fuel.

There are several approaches available for reducing specific fuel burn, through improvements to both aircraft and engines. These include lower airframe-engine weight (lighter materials), reduced airframe/engine drag (aerodynamic improvements) and lower engine specific fuel consumption (SFC). Improved engine SFC can be achieved through both thermal and/or propulsive efficiency (Section II-A). In practice, manufacturers have progressed along both routes: examples being thermal efficiency improvements through advances in high temperature materials and cooling systems; propulsive efficiency through higher bypass ratios.

There has been steady improvement in fuel efficiency over the decades since the introduction of civil jet aircraft in the late 1950's (Figure III-A-1). Compared to those

early jet aircraft, today's have a 70% higher fuel efficiency, about 40% of which is due to the engine and 30% to the airframe.

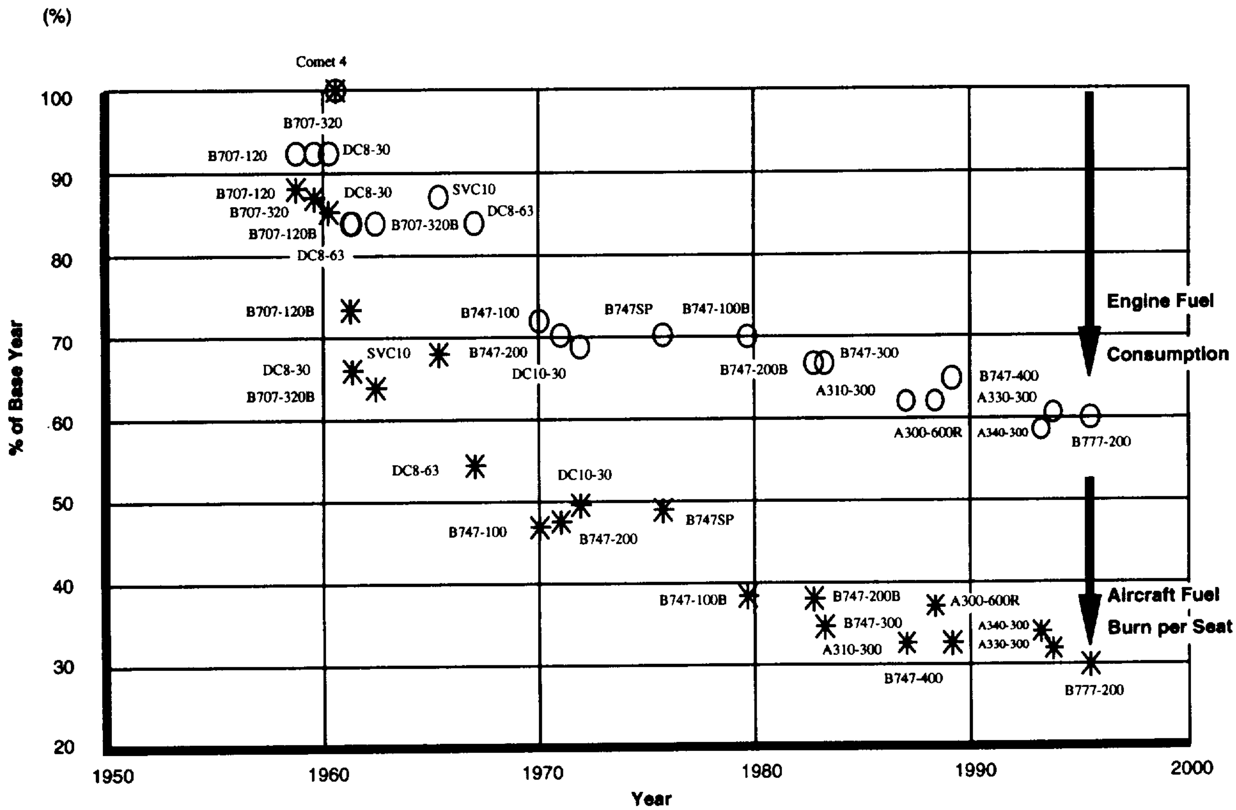

Figure III - A -1 Fuel Efficiency Improvements of Long-Range Transport Aircraft (Rolls Royce plc)

The benefits of this efficiency are lower emissions of CO_2 and H_2O (as well as SO_x from the fuel sulphur). The trend is levelling out, but there is some scope for further improvements although engine related moves in this direction make NO_x control more challenging. In comparison with alternative modes of transportation, such as automobiles, modern short haul aircraft produce, on a per passenger-kilometre basis, about the same CO_2, slightly more NO_x and much less CO and HC (the latter three presume an effective 3-way catalytic converter on the car). The comparison is clearly heavily dependent on load factors.

NO_x emissions are fundamentally influenced by the flame temperature and residence time in the combustion zone. The chemical and physical principles are well understood. The engineering approaches to NO_x reduction involve <u>both</u> the available technology base for combustor design <u>and</u> the overall engine cycle considerations.

Progress in combustor technology has been twofold (Figure III-A-2). The first

has been design stoichiometry optimisation for current conventional single annular combustor (SAC). Here, improvements are generally through incremental changes to known and proven technology, for example the RB211 evolution to the Trent engine. In conjunction with other engine design improvements, this has resulted in only relatively small increases in per-engine $EINO_x$ emissions over the last three decades. The second concerns the design philosophy for advanced combustors, including fuel staged types, e.g. the CFM56 single to double annular and the V2500 single annular to axially staged combustors. These potentially offer more dramatic improvements, but at much greater development costs and risk to the manufacturer, due to their complexity and technological immaturity. The first engine types incorporating these fuel staged combustors are only just beginning to enter service. Airline experience is now required to generate confidence that the potential can be realised in practice.

Further research is targeted towards ultra low NO_x combustors for a possible future second generation supersonic aircraft as well as incorporation of similar concepts into advanced subsonic aircraft.

The impact of engine cycle considerations has already been discussed. While it may not, at this time, be possible to define a realistic optimisation from all points of view of engine cycle, efficiencies and NO_x, the important point is that there is no single relationship between CO_2 and NO_x that holds for all engine types - for a given engine cycle design, i.e., fuel efficiency and CO_2, different combustor design concepts with significantly different NO_x levels could be incorporated.

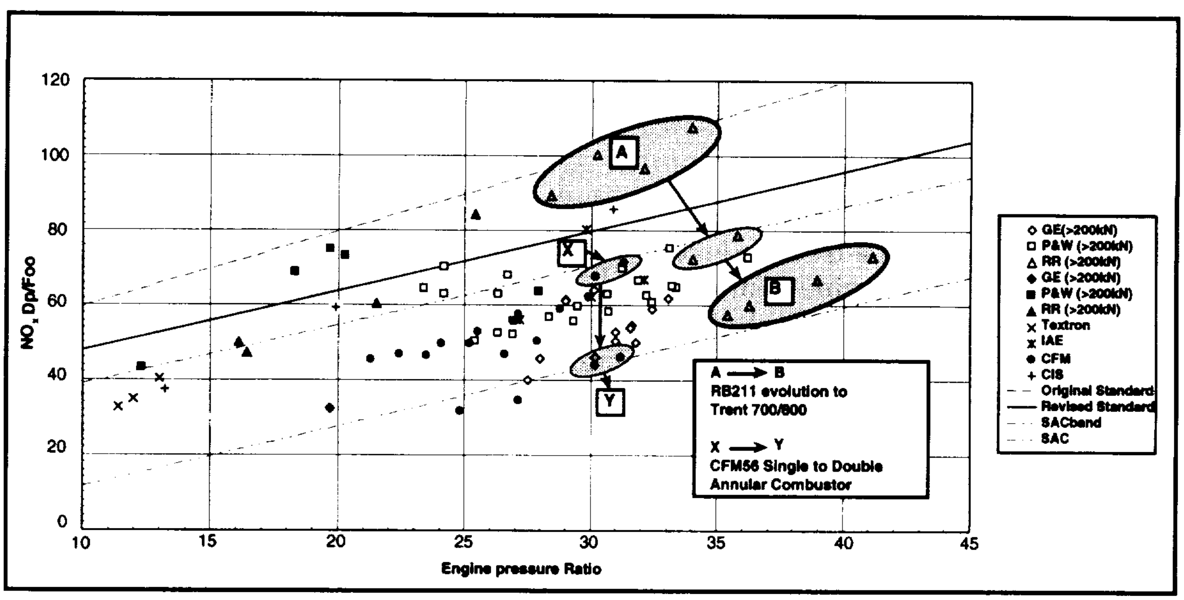

Figure III-A-2 Nitrogen Oxide Emissions Versus Engine Pressure Ratio for Various Engines

Aerosols and particulates are a much less well defined and understood topic. The combustion process oxidises the sulphur in the fuel and produces soot particulates and NO_x. In a complex set of reactions and condensations through the turbine nozzle, exhaust plume and wake, these can generate aerosols. It is believed that these may serve as condensation nuclei affecting cloud formation, and as surfaces for heterogeneous chemistry. There are major uncertainties over the composition of the particulates and speciation of the sulphur compounds, which requires further research.

If shown to be necessary, fuel sulphur could be removed, at a cost, but would introduce other difficulties for engines (Section II-A). Soot (smoke) is currently regulated for the LTO cycle, but would need further research to reduce it much.

From an overall technology point of view, manufacturers will continue to be driven by market forces for fuel efficiency. As regards reduction of NO_x (and other emissions) they are seeking clear definition of need and emergence of the appropriate regulatory theme.

Air Traffic Management (ATM)

The present world wide air navigation system has evolved at local, national and regional levels and is largely dictated by issues of sovereignty and national requirements. As a result, there is not an optimum use of air space. Aircraft fly along defined routes in accordance with previously filed and approved flight plans and as instructed by air traffic controllers. It is the controller's task to keep aircraft in the system separated from one another.

Controllers and pilots use different tools, for communication, navigation and surveillance (CNS) to accomplish their objectives. These systems are primarily ground based and restricted to line of sight, which limits their accuracy. They are maintenance intensive and the communication systems are voice only. These severe limitations are now being addressed on a global scale within the ICAO framework.

It is the goal of ICAO and Member States to see evolution from the current system towards a fully integrated global system. Such a system is now emerging (CNS-ATM), making use of advances in digital communications technology and satellite systems. Performance criteria will allow the providers and users of airspace to determine the optimum manner of its use, e.g., point-to-point flights. CNS-ATM will not just provide large incremental improvements in the service already provided locally, nationally and regionally, but will also be adaptable to changing traffic conditions. Ultimately the improvements will result in lower fuel use, whilst allowing higher traffic volumes in heavily flown corridors. These trends are already emerging.

ATM is at a revolutionary point in time. As many of the standards and procedures that will govern the future system have not yet been developed, there are opportunities to work together to examine the future impact and consequences. From an environmental perspective, these ATM measures to reduce fuel <u>use</u> are beneficial,

but only as part of the operational issues debate. Reducing the impact of fuel use (effect of emissions) may well require different operational practice, e.g., restricting routes to non-sensitive regions, widening flight corridors and repositioning them in response to meteorology, reducing cruise altitudes. These could increase fuel use significantly and a balance between environmental impact, economics, etc., will be needed. With the opening up of new, more direct routes, for example over Siberia, this balance needs careful study, especially as many nations view airspace as a resource.

Key Points

1. *Significant fuel efficiency improvements in both aircraft and engines have been achieved over the last few decades but these are levelling out.* Some new technologies have been identified, having a potentially large impact on fuel efficiency, but are not commercial propositions at present.

2. *Fuel efficiency improvements and better operational practices will not compensate for the extra total fuel use, and hence emissions generated by anticipated traffic growth.* The only way to minimise growth of CO_2 and H_2O emissions is to restrict traffic growth and/or develop appropriate technology solutions.

3. *There are at present no practical, economically viable, alternatives to the use of aviation kerosene.* Other candidate fuels may reduce or eliminate CO_2. Such fuels will increase H_2O emissions.

4. *Improvements in engine fuel efficiency through higher thermal efficiencies make NO_x control more difficult.* Higher thermal efficiencies are the consequence of higher core temperatures and pressures, which, without further technology improvements, lead to higher NO_x emissions, thus tending to offset the NO_x reductions arising from the improved SFC.

5. *Significant NO_x technology improvements have been made and incorporated into current engines.* Despite big increases in core temperatures and pressures, there have only been relatively small NO_x increases over the past 30 years, compared to the increases which would have occurred without the technology improvements.

6. *There is no absolute relationship between CO_2 and NO_x that holds for all engines.* CO_2 is a function of the engine cycle selected whilst NO_x is dependent on the level of combustor technology incorporated into the engine.

7. *Improvements to Air Traffic Management practices, e.g., direct flights have the potential to decrease fuel use.* This potential is probably equivalent to a few years of anticipated traffic growth.

8. *Operational practices, optimised to minimise fuel use, will also reduce emissions but there are possible conflicts between measures to reduce total fuel use and measures to reduce the impact of fuel use.* They may also reduce fuel use, but may concentrate (increase) emissions in specific flight corridors, or place emissions into environmentally sensitive regions, with potentially greater environmental impact. Alternative routing to avoid environmentally sensitive regions may increase fuel use.

9. *Environmental levies are a means of encouraging adoption of improved technology, ATM and operational practices.* Some States are exploring the introduction of environmental levies on air transport. According to established ICAO policy, if States do introduce such levies, they should be as charges for improving the aviation infrastructure, not taxes for the general treasury.

Principal contributors to the session on Control of Emissions

Rich Niedzwiecki:	Session Chair
Reiner Dunker:	Rapporteur
John Koshoffer:	NO_x control
David Snape:	Fuel efficiency: CO_2/H_2O control
Chuck Kolb:	Aerosols and Particulates
Vincent Galotti:	Air Traffic Management
John Crayston:	Charges and Taxes
Malcolm Ralph:	Operational Impacts
Giovanni Angeletti:	Provocateur

B. Where Do We Go From Here?

As was noted early in the Symposium, an integrated state-of-understanding assessment of the atmospheric impacts and technological and economic aspects of the issue has not been done in an integrated fashion. Indeed, the Symposium was intended to be an impetus toward achieving this product.

Presentations and discussions underscored several preferred aspects of such an assessment:

Scope

- *It should address both supersonic and subsonic aircraft.* Such state-of-understanding statements are (or likely will be) needed in the next 2 - 6 years. For example, industry may focus on a go/no-go decision with regard to a new generation of supersonic civil transport shortly after the year 2000. Further, governments are already debating the desirability of more stringent NO_x-emission controls for subsonic aircraft.

- *It should include (and aim to integrate) the atmospheric science, technology, and economics of the issue.* All are needed to characterise the problem and to lay out, as quantified as possible, the possible options for amelioration. For example: CO_2, NO_x, particles, and sulphur - How are they related in the atmosphere and how are they related in engines?

- *It should address both ozone-layer depletion and radiative forcing of climate change.* These are related in the atmosphere. Aircraft emissions influence both. For example, stratospheric ozone depletion introduces a cooling tendency in the tropospheric climate system. Further, the sign of both ozone changes and radiative-forcing changes are sensitive to altitude, which is a point of key significance in the aircraft issue.

Timing

Existing efforts: Several research programs (see Appendix D) have review endeavours underway whose content and timing relate to the larger assessment picture:

> *European Commission.* Assessment by European researchers of atmospheric impacts (ozone layer and radiation forcing) of supersonic and subsonic aircraft. Publication in early-1997 as an EC report and as a major review paper in a scientific journal.

> *National Aeronautics and Space Administration.* Assessment by the researchers (primarily US) of the Atmospheric Effects of Aviation Project of (i) the ozone-layer impacts of supersonic transport in 1995 and 1998 and (ii) the atmospheric impacts (ozone layer and radiation forcing) of subsonic aircraft in 1997, 1999, and 2001.

In the Planning Stage: Planning timetables and some future assessment activities have been laid out as follows by three international bodies over the next few years and are diagrammed in Figure III-B-1. The details follow on the next page.

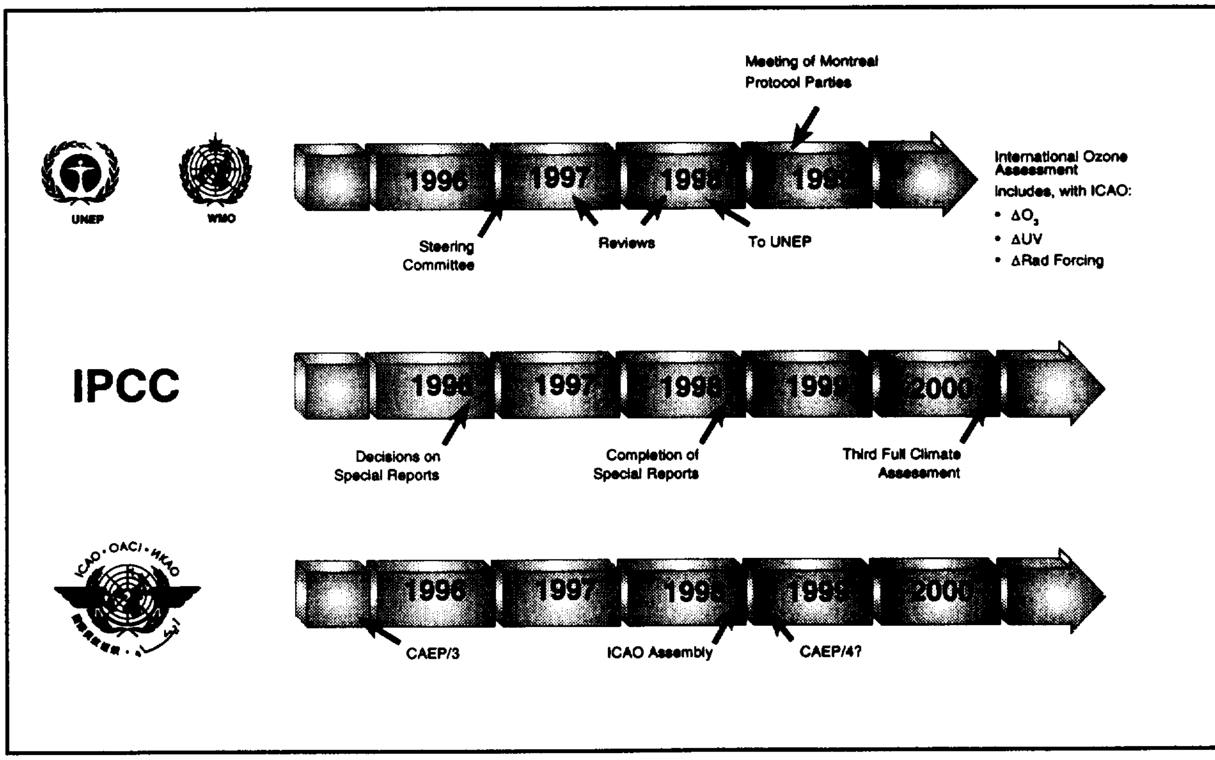

Figure III-B-1. Planning Timetables and Some Future Assessment Activities

Ozone Scientific Panel of the Montreal Protocol. The Parties to the UN Montreal Protocol have requested its Ozone Scientific Panel to prepare another in its series of assessments of the understanding of the depletion of the ozone layer by halocarbons (e.g., chlorofluorocarbons - CFCs). The Parties requested that the assessment also include other aspects of ozone changes, such as the impacts of aircraft emissions. The submission of the updated assessment will be 31 October 1998.

Intergovernmental Panel on Climate Change (IPCC). The IPCC has been requested to consider the possibility of preparing one of its Special Reports on the impacts of aircraft emissions on the global climate system. The IPCC met in Mexico City in September 1996 to decide its work program. They approved a Special Report on Aviation and the Global Atmosphere, to be done in association with the Montreal Protocol Ozone Science Panel and ICAO to be completed in late 1998.

International Civil Aviation Organization (ICAO). ICAO has requested input from IPCC and Montreal Protocol regarding information about the impacts of aviation on the atmosphere. Such information could be part of the considerations for new control on engine emissions. The ICAO Assembly is next scheduled to meet in the time frame of Fall, 1998.

Conclusions

In view of the above information needs and timetables, the Symposium recognised the value of a single international scientific/technical assessment regarding the current understanding of the impacts of aircraft emissions on the global atmosphere. This could be carried out under the auspices of the IPCC, Montreal Protocol Ozone Scientific Panel, and ICAO, with a goal of completion by the Fall of 1998.

Near-term information needs can be addressed by the European Commission and NASA assessments. Long-term information needs could be addressed in the Third Assessment Report planned by the IPCC in the year 2000.

[redacted]

Acknowledgments

This summary report of the proceedings of the symposium was compiled by the organising committee, which assumes full responsibility for its accuracy. The report is based on a record of presentation material and minutes, and was reviewed by session chairpersons. The committee wishes to thank all of the symposium participants for their contribution of expertise, insight, guidance and opinion. Thanks are also owed to Jorge Scientific Corporation, Mr. Christopher Thompson of Science Communications, and Ms. Julie Catloth of the NASA Goddard Space Flight Center for their assistance in conducting the symposium and compilation of the record.

Appendix A
Symposium on the Global Atmospheric Effects of Aviation
Agenda

Sunday, April 14

6:00 p.m.	Registration	
7:00 p.m.	Welcome reception	

Monday, April 15

Introduction

9:00 a.m.	Introduction and logistics	Howard Wesoky
9:15 a.m.	Symposium objectives and agenda	Dave Lister and A.R. Ravishankara
9:45 a.m.	Aviation regulatory standard policy process	John Crayston
10:15 a.m.	Break	
10:45 a.m.	Policy/science interactions and relation to aviation issue	Daniel Albritton
11:30 a.m.	Economic assessment requirements	Michael Mann
12:00 p.m.	Aviation and its impact: A public interest perspective	Michael Oppenheimer
12:30 p.m.	Lunch	

Aircraft, Engines and Emissions

2:00 p.m.	Introduction	Roger Cottington Chairperson Anthony Fiorentino Rapporteur
2:05 p.m.	Tutorial	Donald Bahr
2:30 p.m.	Current Certification Requirements	James Elwood
2:50 p.m.	Future certification	Dave Lister
3:10 p.m.	Discussion	Chairperson and speakers Provocateur: Joel Levy
3:30 p.m.	Break	

Current and Forecast Inventories — Upali Wickrama, Chairperson; Anthony Fiorentino, Rapporteur

4:00 p.m.	Overview	Malcolm Ralph
4:20 p.m.	ANCAT Review	Roger Gardner Alfons Schmitt
4:40 p.m.	NASA review	Steven Baughcum
5:00 p.m.	Discussion	Chairperson and speakers Provocateurs: Chris Hume and Donald Wuebbles
5:30 p.m.		Adjourn

Tuesday, April 16

Tropospheric Ozone: The Newer Issue — Anne Thompson, Chairperson; Hans Schlager, Rapporteur

9:00 a.m.	Tutorial	Guy Brasseur
9:45 a.m.	Discussion	
10:15 a.m.	Aircraft contribution to tropospheric NOx	Frank Arnold
10:45 a.m.	Break	
11:15 a.m.	How well can we calculate tropospheric ozone and aircraft contributions to this abundance	Jennifer Logan
11:45 a.m.	Non-technical summary of issues looked at in-depth and discussion	Chairperson and speakers Provocateur: N. Sundararaman
12:30 p.m.	Lunch	

Stratospheric Ozone: The Original Issue. — Mack McFarland, Chairperson; Dean Peterson, Rapporteur

2:00 p.m.	Tutorial	Roderic Jones
2:45 p.m.	Discussion	
3:00 p.m.	Where we are in understanding effects of supersonic aircraft	David Fahey
3:30 p.m.	Break	
4:00 p.m.	Special role of strat/trop exchange to aircraft issues.	Richard Rood
4:30 p.m.	Stratosphere in the year 2050: Can we predict it?	Richard Stolarski
5:00 p.m.	Non-technical summary of issues looked at in-depth and discussion	Chairperson and speakers Provocateur: Tore Knobloch
6:00 p.m.	Adjourn	

Wednesday, April 17

Greenhouse Gases and Climate: The Emerging Issue		Ivar Isaksen Chairperson Robert Sausen Rapporteur
8:30 a.m.	Tutorial	Robert Cess
9:15 a.m.	Discussion	
9:30 a.m.	Influence of chemistry on greenhouse gases	Jos Lelieveld
10:00 a.m.	Climate consequences of ozone changes in the stratosphere	Marvin Geller
10:30 a.m.	Break	
11:00 a.m.	Relationship of radiative forcing to climate	Michael Prather
11:30 a.m.	Non-technical summary of issues looked at in-depth and discussion	Chairperson and speakers Provocateur: Jan Westerberg
12:30 p.m.	Lunch	

Aerosols, Chemistry and Climate: A New Focus		Hartmut Grassl Chairperson Estelle Condon Rapporteur
2:00 p.m.	Tutorial	Joyce Penner
2:45 p.m.	Discussion	
3:00 p.m.	Cirrus clouds- their connection to climate and aircraft	Brian Toon
3:30 p.m.	Break	
4:00 p.m.	How do aerosols/clouds change composition of radiation?	Bernd Kaercher
4:30 p.m.	Non-technical summary of issues looked at in-depth and discussion	Chairperson and speakers Provocateur: Martin Wright
5:30 p.m.	Adjourn	
6:30 p.m.	Reception	
7:00 p.m.	Dinner	Paul Gray, speaker

Thursday, April 18

9:00 a.m.	Preparatory remarks for Friday Session	Dan Albritton
9:30 a.m.	Summary of overall effects and issues importance of one, factor over the other	Ullrich Schumann
11:00 a.m.	Panel Discussion	Chairperson, M. McFarland A. Thompson A.R. Ravishankara U. Schumann Provocateurs: Al Kaehn and Georgios Amanatidis
12:30 p.m.	Lunch	
Control of Emissions		Richard Niedzwiecki Chairperson Reiner Dunker Rapporteur
2:00 p.m.	NOx control	John Koshoffer

2:30 p.m.	Fuel efficiency:CO2/H20 control	David Snape
3:00 p.m.	Aerosols and particulates	Charles Kolb
3:30 p.m.	Break	
4:00 p.m.	Air traffic management	Vincent Galotti
4:20 p.m.	Operational impacts	Malcolm Ralph
4:40 p.m.	Fiscal measures	John Crayston
5:00 p.m.	Discussion	Chairperson and speakers Provocateur: Giovanni Angeletti
5:30 p.m.	Adjourn	

Friday, April 19

Where Do We Go From Here?

8:30 a.m.	What I heard as it relates to policy	Robert Shuter, Chair Howard Aylesworth James Erickson Jochem Peeters Bengt Olav Nas Tony Rowland
10:00 a.m.	Break	
10:30 a.m.	Assessment strategy • Possible assessment aims and contents • International organizational interests and roles • Planning the symposium report	Daniel Albritton, Chair Howard Wesoky Dave Lister Mack McFarland Paul Gray John Crayston
12:00 p.m.	Adjourn	

APPENDIX B:
Symposium on the Global Environmental Effects of Aviation
April 15-19, 1996
Participant List

1 **J. Ken Adams**
Woodend Drive
Cairns Cottage
Ascot, Berks SL5 9BD
United Kingdom
Phone: +44 134-422-651 **E-Mail:**
Fax: +44 134-487-2009

2 **Daniel L. Albritton**
R/E/AL
Aeronomy Laboratory
National Oceanic and Atmospheric Administration
325 Broadway
Boulder CO 80303-3328
Phone: 303 497-3134 **E-Mail:** aldiroff@al.noaa.gov
Fax: 303 497-5340

3 **Georgios T Amanatidis**
DGXII/D-1
Rue de La Loi 200
Commission of the European Union
B-1049 Brussels
Belgium
Phone: 32- 2-295 88 15 **E-Mail:** g.amanatidis@mhsg.cec.be
Fax: 32- 2-296 30 24

4 **James Anderson**
Department of Chemistry
12 Oxford Street, Link Rm. 268
Harvard University
Cambridge MA 02138
Phone: 617 495-5922 **E-Mail:** anderson@huarp.harvard.edu
Fax: 617 495-4902

5 **Giovanni Angeletti**
DGXII/D-1
Rue de La Loi 200
Commission of the European Union
B-1049 Brussels
Belgium
Phone: 32- 2-295 84 32 **E-Mail:** giovanni.angeletti@dg12.cec.be
Fax: 32- 2-296 30 24

6 **Frank Arnold**
Atmospheric Physics Division
PO Box 103980
Max-Planck-Institute for Nuclear Physics
Heidelberg D-69029
Germany
Phone: 49 6221 516467 **E-Mail:**
Fax: +49 6221 516324

7 **Howard Aylesworth**
1250 Eye Street, NW
Aerospace Industries Assocation of America
Washington DC 20005
Phone: 202 371-8456 **E-Mail:**
Fax: 202 371-8471

8 **Donald W. Bahr**
6576 Brandford Court
Panel on Atmospheric Effects of Aviation
Cincinnati OH 45236
Phone: 513 793-3685 **E-Mail:**
Fax: 513 793-6506

9 **Steven Baughcum**
PO Box 3707
MS 6H-FC
Boeing Co.
Seattle WA 98124
Phone: 206 965-0426 **E-Mail:** baughcum@atc.boeing.com
Fax: 206 234-4543

10 **Darrel Baumgardner**
Atmospheric Technology Division
1850 Table Mesa Drive
National Center for Atmospheric Research
PO Box 3000
Boulder CO 90307-3000
Phone: 303 497-1054 **E-Mail:** darrel@ncar.ucar.edu
Fax: 303 497-1092

11 **John Begin**
5105 Northwest Drive
C1125
Northwest Airlines
St. Paul MN 55111-3034
Phone: 612 726-7390 **E-Mail:**
Fax: 612 727-4845

12 **John D. Bradshaw**
Baker Building, Room 107
923 Dalney Street
Georgia Institute of Technology
Atlanta GA 30332-0340
Phone: 404 894-3895 **E-Mail:** jb57@prism.gatech.edu
Fax: 404 894-6670

13 **Guy Brasseur**
Service d'Aeronomie
B.P. n°3
CNRS
91371 Verrieres-le-Buisson
France
Phone: +33 1-64474347 **E-Mail:** brasseur@ncar.ucar.edu
Fax: +33 1-64474348

14 **Norbert Brehm**
Eschenweg 11
BMW/Rolls Royce
D-15827 Dahlewitz
Germany
Phone: 49 33708-61433 **E-Mail:**
Fax: +49 33708-63279

15 **Werner Bula**
Maulbeerstrasse 9
Office Federal de l'Aviation Civile
CH-3003 Berne
Switzerland
Phone: +41 31-325-9110 **E-Mail:**
Fax: +41 31-325-9212

16 **Pablo Osvaldo Canziani**
Aranguren 342
University of Buenos Aires
1428 Buenos Aires
Argentina
Phone: **E-Mail:** osvaldo@atmos.washington.edu
Fax: 54 1-783-3098

17 **Julie Catloth**
Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301 286-7912 **E-Mail:** catloth@polska.gsfc.nasa.gov
Fax: 301 286-1754

18 **Robert Cess**
Marine Sciences Research Center
SUNY Stonybrook
Stonybrook NY 11794-5000
Phone: 516 632-8321 **E-Mail:** cess@atmsci.msrc.sunysb.edu
Fax: 516 632-8379

19 **Ronald Cohen**
Atmospheric Research Project
Engineering Sciences Laboratory
Harvard University
12 Oxford Street
Cambridge MA 02138
Phone: 617 495-5922 **E-Mail:** cohen@huarp.harvard.edu
Fax: 617 495-4902

20 **Graham Coleman**
P161 Building
Farnborough, Hants
DRA
GU14 OLS
nited Kingdom
Phone: +44 1252-392440 **E-Mail:**
Fax: +44 1252-392409

21 **Estelle Condon**
Mail Stop 239-20
NASA/Ames Research Center
Moffett Field CA 94035-1000
Phone: 415 604-6071 **E-Mail:** estelle_condon@sggate.arc.nasa.gov
Fax: 415 604-1088

22 **Roger Cottington**
170 Building
DTEO Pyestock
DRA
Farnborough, Hants
GU14 OLD
United Kingdom
Phone: +44 1252-374203 **E-Mail:**
Fax: +44 1252-372477

23 **John Crayston**
Suite 400
1000 Sherbrooke Street West
International Civil Aviation Organization
Montreal, Quebec H3A 2R2
Canada
Phone: 514 954-6371 **E-Mail:** jcrayston@icao.org
Fax: 514 954-6744

24 **David Crosley**
Molecula Physics Laboratory
333 Ravenwood Avenue
SRI International
Menlo Park CA 94025
Phone: 415 859-2395 **E-Mail:** drc@mplvax.sri.com
Fax: 415 859-6196

25 **Anne Douglass**
Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301- 286-2337 **E-Mail:** douglass@persephone.gsfc.nasa.gov
Fax: 301- 286-1662

26 **Manvendra Dubey**
333 Ravenswood Ave
SRI International
Menlo Park CA 94025
Phone: 415 859-2048 **E-Mail:**
Fax: 415 859-6196

27 **Reiner Dunker**
DGXII/C-3
Rue de La Loi 200
Commission of the European Union
B-1049 Brussels
Belgium
Phone: 32- 1-2124-61608 **E-Mail:**
Fax: 32- 1-29-667-57

28 **Elizabeth J. Duthie**
Head, CA4 Division
Zone 2/27 Great Mister House
Department of Transport
76 Marsham Street
London, SW1P 4DR
United Kingdom
Phone: +44 171 271 4868 **E-Mail:**
Fax: +44 171 271 4907

29 **Jim Elwood**
23 Scott Drive
South Windsor CT 06074
Phone: 860 644-2150 **E-Mail:** internet:72242.3016@compuserve.con
Fax: 860 644-2150

30 **James Erickson**
AEE-1
800 Independence Ave., SW
FAA, Office of Environment & Energy
Washington DC 20591
Phone: 202 267-3576 **E-Mail:**
Fax: 202 267-5594

31 **Peter Fabian**
Waldvogeleinstr. 3
University of Munich
D-80995 Munchen
Germany
Phone: +49 89-150-7639 **E-Mail:** fabian@physik.uni-bremen.de
Fax: +49 89-150-7639

32 **David W. Fahey**
Aeronomy Laboratory
325 Broadway
NOAA/ERL
R/E/AL6, Bldg. 24
Boulder CO 80303
Phone: 303 497-5277 **E-Mail:** fahey@al.noaa.gov
Fax: 303 497-5373

33 **Joseph Farman**
c/o British Antartic Survey
Madingley Road
European Ozone Research Coodinating Unit
Cambridge CB3 OET
United Kingdom
Phone: 44 1-223-251631 **E-Mail:** u_hjm@vc.nbs.ac.uk
Fax: 44 1-223-467390

34 **Anthony Fiorentino**
400 Main Street
Pratt & Whitney
E. Hartford CT 06108
Phone: 203 565-2798 **E-Mail:** fiorena@pweh.com
Fax: 203 565-4017

35 **Randall Friedl**
Code YS
NASA Headquarters
Washington DC 20546-0001
Phone: 202 358-0776 **E-Mail:**
Fax: 202 358-2770

36 **Vincent Galotti**
ATM Section
1000 Sherbrooke Street West
International Civil Aviation Organization
Montreal, Quebec H3A 2R2
Canada
Phone: 514 285-6711 **E-Mail:** 103010.1721@compuserve.com
Fax: 514 285-6759

37 **Roger Gardner**
Civil Aviation Division 4
Rm S9/01
UK/DOT
2 Marsham Street
London SW1P 3EB
United Kingdom
Phone: 44 11-276-5331 **E-Mail:**
Fax: 44 171-271-4907

38 **Alice Gaustad**
Executive Adviser, International Relations
Civil Aviation Administration
ICAO
PO Box 8124 Dep
Oslo N-0032
Norway
Phone: 47 22 94 23 48 **E-Mail:**
Fax: 47 22-94-23-97

39 **Marvin A. Geller**
ITPA/MSRC
125 Endeavour Hall
Suny
Stony Brook NY 11794-5000
Phone: 516 632-6170 **E-Mail:** mgeller@ccmail.sunysb.edu
Fax: 516 632-6251

40 **Hartmut Grassl**
Bundesstrasse 55
Max-Planke Institute fur Meteorologie
2000 Hamburg 13
Germany
Phone: 49 40-411 73225 **E-Mail:**
Fax: +49 40-411 73298

41 **Paul Gray**
DGXII/D
Rue de La Loi 200
Commission of the European Union
B-1049 Brussels
Belgium
Phone: 32- 2-295-1815 or 4070 **E-Mail:** p.gray@mhsg.cec.be
Fax: 32- 2-295-3024

42 **William Grose**
MS 401B
NASA/LaRC
Hampton VA 23665
Phone: 804 864-5820 **E-Mail:** grose@haloe.larc.nasa.gov
Fax: 804 864-8543

43 **Didier Guffond**
8 rue des Vertugadins
ONERA/AEREA
Meudon 92190
France
Phone: 33 1-46-23-51-83 **E-Mail:** guffond@onera.fr
Fax: 33 1-46-23-50-61

44 **Kevin Gurchak**
Pittsburgh International Airport
M/S PIT/AA355
US Air
Pittsburgh PA 15231
Phone: 412 472-1519 **E-Mail:**
Fax: 412 472-1510

45 **Garry Hayman**
AEA Technology
E5 Culham
National Environmental Technology Centre
Abingdon, Oxon OX14 3DB
UK
Phone: +44 1-235-463108 **E-Mail:** garry.hayman@aeat.co.uk
Fax: +44 1-235-463005

46 **Stephen C. Henderson**
Mail Stop 68-19
PO Box 3707
Boeing Commercial Airplane Group
Seattle WA 98124-2207
Phone: 206 237-8905 **E-Mail:** baughcum@atc.boeing.com
Fax: 206 237-1706

47 **John Hennigan**
Room 939
800 Independence Avenue SW
Federal Aviation Administration
Washington DC 20591
Phone: 202 267-3276 **E-Mail:**
Fax: 202 267-3324

48 **Erika Herms**
246 rue Lecourbe
Direction Generale de l'Aviation Civile - France
75015 Paris
France
Phone: +33 140435598 **E-Mail:**
Fax: +33 140435802

49 **Robert Howard**
1099 Avenue C
Sverdrup Technology, Inc.
Arnold AFB TN 37389-9013
Phone: 615 454-4783 **E-Mail:** howard@hap.arnold.af.mil
Fax: 615 454-6317

50 **Chris Hume**
Department B57
New Filton House
British Aerospace Airbus Limited
Bristol Avon BS99 7AR
United Kingdom
Phone: 44 117 936 2484 **E-Mail:**
Fax: 44 117 936 5217

51 **Ivar Isaksen**
P.B. 10220315 Blindern
University of Oslo
Oslo
Norway
Phone: +47 22 855 822 **E-Mail:** ivar.isaksen@geofysik.uio.no
Fax: +47 22 855 269

52 **Charles H. Jackman**
Mail Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301 286-8399 **E-Mail:** jackman@assess.gsfc.nasa.gov
Fax: 301 286-1662

53 **Roderic L. Jones**
Department of Chemistry
Center for Atmospheric Science
University of Cambridge
Lensfield Road
Cambridge CB2 1EW
United Kingdom
Phone: 44 223-336466 **E-Mail:** rlj1001@cam.ac.uk
Fax: 44 1-223-336362

54 **Albert J. Kaehn**
9514 Kirkfield Road
Panel on Atmosheric Effects of Aviation
Burke VA 22015
Phone: 703 323-7713 **E-Mail:**
Fax: 703

55 **Bernd Kaercher**
Hohenbacherstr 22
Universitat Muenchen
D-85354 Freising
Germany
Phone: +49 8761 714742 **E-Mail:** brk@armos1.met.forst.uni-muench
Fax: +49 8161 714753

56 **M. Paul Kang**
AEE-110
800 Independence Avenue, SW
Federal Aviation Administration
Washington, DC 20591
Phone: 202 267-3566 **E-Mail:** pkang@mail.hq.faa.gov
Fax: 202 267-5594

57 **Hennie Kelder**
Department of Physical Meteorology
P.O. Box 201
Royal Netherlands Meteorological Institute
3730 AE De Bilt
Wilhelminalaan 10
The Netherlands
Phone: 31 30-206-472 **E-Mail:** kelder@knmi.nl
Fax: 31 30-210-407

58 **Richard Ketler**
Suite 100
1301 Pennsylvania Avenue, NW
Air Transport Association of America
Washington DC 20004-1707
Phone: 202 626-4155 **E-Mail:**
Fax: 202 626-4139

59 **Barry Kiel**
1790 Loop Road North, Bldg. 490
WL/POSC
USAF/Wright Laboratory
Wright Patterson AFB OH 45433-7103
Phone: 513 255-7487 **E-Mail:** beaver@ward.appl.wpafb.af.mil
Fax: 513 255-1125

60 **Douglas E. Kinnison**
Global Climate Research Division, L-262
7000 East Avenue
Lawrence Livermore Laboratory
PO Box 808
Livermore CA 94550-9900
Phone: 510 422-7975 **E-Mail:** kinnison1@llnl.gov
Fax: 510 422-5844

61 **T. P. Knobloch**
Nature Conservation
Nuclear and Safety
Ministry of Environment
Bernkasteler Strasse 8
53048 Bonn
Germany
Phone: +49 228-305-2470 **E-Mail:**
Fax: +49 228-305-3524

62 **Charles Kolb**
45 Manning Road
Aerodyne Research, Inc.
Billerica MA 01821-3976
Phone: 508 663-9500 x290 **E-Mail:** kolb@aerodyne.com
Fax: 508 663-4918

63 **John M. Koshoffer**
790 Carini Lane
General Electric
Cincinnatti OH 45218-1510
Phone: 513 243-2955 **E-Mail:** john.m.koshoffer@ae.ge.com
Fax: 513 243-2541

64 **Manfred Lecht**
Institute of Propulsion Technology
Linder Hohe
DLR
D-51147 Koeln
Germany
Phone: +49 2203 6010, x-2081 **E-Mail:**
Fax: +49 2203 64395

65 **Jos Lelieveld**
(IMAU)
Princeton Plein 5
Institute for Marine & Atmospheric Research Utrecht
PO Box 80005
3508 TA Utrecht
The Netherlands
Phone: 31 30 253-2921 **E-Mail:** lelieveld@fys.ruu.nl
Fax: 31 30-254-3163

66 **Joel Levy**
Mailcode GP
Office of Global Programs
NOAA/Office of Oceanic & Atmospheric Research
1100 Wayne Avenue, Ste 1225
Silver Spring MD 20910
Phone: 301 427-2089 **E-Mail:** levy@ogp.noaa.gov
Fax: 301 427-2082

67 **Harvey Lilenfeld**
MC 111-1041
PO Box 516
McDonnell Douglas
St. Louis MO 63166
Phone: 314 233-2550 **E-Mail:** hlilenfeld@gwsmtp01.mdc.com
Fax: 314 232-0888

68 **Dave H. Lister**
Propulsion Technology Department
170 Building
DRA Pyestock
Farnborough, HANTS, GU14 OLS
United Kingdom
Phone: 44- 1252-374217 **E-Mail:** dhlister@dra.hmg.gb
Fax: 44- 1252-372477

69 **Shaw Liu**
School of Earth and Atmospheric Sciences
221 Bobby Dodd Way
Georgia Institute of Technology
Atlanta GA 30332-0340
Phone: 404 894-1758 **E-Mail:** liu@al.noaa.gov - thru 3/14
Fax: 404 894-1106

70 **Jennifer Logan**
108 Pierce Hall
29 Oxford Street
Harvard University
Cambridge MA 02138
Phone: 617 495-4582 **E-Mail:** jal@europa.harvard.edu
Fax: 617 495-9837

71 **Lee Lopes**
DOP
877 Avenue E, Ste 108
USAF/Arnold Eng. Devel. Ctr.
Arnold AFB TN 37389-5050
Phone: 615 454-5949 **E-Mail:** lopes@hap.arnold.af.mil
Fax: 615 454-4327

72 **Stephen Lukachko**
Aero-Environmental Research Lab
77 Massachusetts Ave
MIT
Bldg. 31-215
Cambridge MA 02139
Phone: **E-Mail:**
Fax:

73 **Suhas Chandra Majumdar**
NPL Campus
CSIR Complex, National Physical Laboratory
Pusa, Delhi 110 012
India
Phone: 91 11-5737953 **E-Mail:** inrist@giasd101.vsnl.net.in
Fax: 91

74 **Michael Mann**
Great Minister House, Rm. 2/33
76, Marsham Street
Department of Transport
London SW1P 4DR
United Kingdom
Phone: +44 0171-271-4928 **E-Mail:**
Fax: +44 1-71-271-4956

75 **Takayo Matsuo**
Japan Climatic Data Centre
1-3-4 Otemachi, Chiyoda-ku
Japan Meteorological Agency
Tokyo 100
Japan
Phone: +81 03 3211 4640 **E-Mail:** matsuo@hq.kishou.go.jp
Fax: +81 03- 3211 4640

76 **Mack McFarland**
PO Box 30552
UNEP
Nairobi
Kenya
Phone: 254 2 624215 **E-Mail:** mack.mcfarland@unep.no
Fax: 254 2 623410

77 **Don McLeay**
P.O. Box 9000
Air Canada
Montreal, Quebec H4Y 1C2
Canada
Phone: 514 422-6824 **E-Mail:**
Fax: 514 422-7606

78 **Munir Metwally**
2401 E. Wardlow Rd.
M/C 71-30
McDonnell Douglas
Long Beach CA 90807-4418
Phone: 310 593-3935 **E-Mail:** mmetwally@mdta.mdc.com
Fax: 310 982-7383

79 **Richard Miake-Lye**
45 Manning Road
Aerodyne Research Inc.
Billerica MA 01821-3976
Phone: 508 663-9500 **E-Mail:** rick@aerodyne.com
Fax: 508 663-4918

80 **P Miller**
(DE/AVT)
British Defense Staff
British Embassy
3100 Massachusetts Avenue, NW
Washington DC 20008
Phone: **E-Mail:**
Fax:

81 **John Montgomery**
P.O. Box 619616 - MD5425
Environmental Department
American Airlines
DFW Airport TX 75261
Phone: **E-Mail:** john_montgomery@amrcorp.com
Fax:

82 **Kevin Moore**
1601 Massachusetts Avenue NW
Embassy of Australia
Washington DC 20036
Phone: 202 797-3228 **E-Mail:**
Fax: 202 667-2119

83 **Alan Mortlock**
2401 E. Wardlow Rd
M/C 71-30
McDonnell Douglas
Long Beach CA 90807-4418
Phone: 310 593-3937 **E-Mail:** mortlock@mdta.mdc.com
Fax: 310 982-7787

84 **Jim Muldoon**
800 Independence Ave, SW
FAA
Washington DC 20591
Phone: 202 267-7513 **E-Mail:**
Fax: 202 267-5594

85 **Bengt Olov Nas**
Frosundaviksalle 1, Solna
Department STOGR
Scandinavian Airlines System (IATA)
S-195 87 Stockholm
Sweden
Phone: +46 8-797 1611 **E-Mail:** bengt.olov.nas@sas.se
Fax: +46 8-857 980

86 **Cindy Newberg**
Stratospheric Protection Division
Office of Air and Radiation
Environmental Protection Agency
401 M Street, SW
Washington DC 20460
Phone: **E-Mail:**
Fax:

87 **Rich Niedzwiecki**
Mail Stop 77-10
2100 Brookpark Road
NASA/Lewis Reseach Center
Cleveland OH 44135-3191
Phone: 216 433-3901 **E-Mail:** psnied@lims01.lerc.nasa.gov
Fax: 216 433-3954

88 **Volker Nitsche**
Flughafen Dusseldorf GMBH
Dusseldorf Airport
Airports Council International
P.O. Box 300363
Dusseldorf D-40403
Germany
Phone: +49 211 421 2532 **E-Mail:**
Fax: +49 211 421 2832

89 **George Novak**
1054 "31st" Street, NW
GKMG
Washington DC 20007
Phone: 202 342-5289 **E-Mail:** avlaw@aol.com
Fax: 202 342-5219

90 **Thomas Odell**
PO Box 3708, MS 68-19
Boeing Commerical Airplane Group
Seattle WA 98124-2207
Phone: 206 237-1475 **E-Mail:**
Fax: 206 237-6368

91 **Toshihiro Ogawa**
Department of Earth and Planetary Physics
Graduate School of Sciences
University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113
Japan
Phone: 81 3-3815-8020 **E-Mail:** ogawa@frl.s.u-tokyo.ac.jp
Fax: 81 3-3818-0745

92 **Michael Oppenheimer**
257 Park Avenue South
16th Floor
Environmental Defense Fund
New York NY 10010
Phone: 212 505-2100 **E-Mail:** michael@edf.org
Fax: 212 505-2375

93 **Joshem Peeters**
P.O. Box 30945
Ministry of Environment
The Hague 25009X
The Netherlands
Phone: +31 70 3394529 **E-Mail:**
Fax: +31 70 3391281

94 **Joyce Penner**
Global Climate Research Division
7000 East Avenue
Lawrence Livermore Laboratory
P.O. Box 808
Livermore CA 94550-9900
Phone: 510 422-4140 **E-Mail:** penner1@llnl.gov
Fax: 510 422-5844

95 **Dean Peterson**
Code Y
NASA Headquarters
Washington DC 20546-0001
Phone: 202 358-0243 **E-Mail:** @hq.nasa.gov
Fax: 202 358-2771

96 **Annie Petsonk**
1875 Connecticut Avenue, NW
Ste 1016
Environmental Defense Fund
Washington DC 20009
Phone: 202 387-3500 **E-Mail:** annie@edf.org
Fax: 202 234-6049

97 **Lamont Poole**
MS 475
NASA/Langley Research Center
Hampton VA 23681-0001
Phone: 804 864-2689 **E-Mail:** l.r.poole@larc.nasa.gov
Fax: 804 864-2671

98 **Michael Prather**
Department of Earth System Science
University of California, Irvine
Irvine CA 92717-3100
Phone: 714 824-5838 **E-Mail:** mprather@uci.edu
Fax: 714 824-3256

99 **Malcolm O. Ralph**
Aerospace Division
Head Branch 3
Department of Trade and Industry/UK
151 Buckingham Palace Road
London SW1 W9SS
United Kingdom
Phone: 44 171 215 1129 **E-Mail:**
Fax: 44 171 215 1180

100 **A. R. Ravishankara**
Aeronomy Laboratory
325 Broadway
NOAA
Boulder CO 80303-3328
Phone: 303 497-5821 **E-Mail:** ravi@al.noaa.gov
Fax: 303 497-5822

101 **Juan Rivera**
Code RH
NASA Headquarters
Washington DC 20546-0001
Phone: 202 358-0761 **E-Mail:** jrivera@aeromail.hq.nasa.gov
Fax: 202 358-3557

102 **Jose M. Rodriguez**
840 Memorial Drive
Atmospheric and Environmental Research, Inc.
Cambridge MA 02139
Phone: 617 547-6207 or 617/349-2255 **E-Mail:** jose@aer.com
Fax: 617 661-6479

103 **Richard B. Rood**
Code 910.3
NASA/Goddard Space Flight Center
Greenbelt MD 20771-0001
Phone: 301 286-8203 **E-Mail:** rood@dao.gsfc.nasa.gov
Fax: 301 286-1754

104 **Douglas Rotman**
Global Climate Research Division, L-262
7000 East Avenue
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore CA 94550-9900
Phone: 510 422-7746 **E-Mail:** drotman@llnl.gov
Fax: 510 422-5844

105 **Anthony Rowland**
DGXI/D-3
Rue de La Loi 200
Commission of the European Union
B-1049 Brussels
Belgium
Phone: 32- 2-296-8709 **E-Mail:**
Fax: 32- 2-296-9554

106 **Keith R. Ryan**
Division of Applied Physics
P.O. Box 218
CSIRO
Lindfield, New South Wales 2070
AUSTRALIA
Phone: +61 2-413-7352 **E-Mail:** keith@dap.csiro.au
Fax: +61 2-413-7204

107 **Nelson Sabogal**
P.O. Box 30552
UNEP/Ozone Secretariat
Nairobi
Kenya
Phone: 254-2-623856 **E-Mail:** Nelson.Sabogal@unep.no
Fax: 254 2-521930

108 **Alfredo Iglesias Sastre**
PL/S 2van de la Cruz S/N - 28070
Direcion General de Aviacion Civil
Madrid
Spain
Phone: +34 1-5976867 **E-Mail:**
Fax: +34 1-5976853

109 **Robert Sausen**
Institut fur Physik der Atmosphare
Munchner Street 20
DLR Oberpfaffenhofen
D-B2234 Wessling
Germany
Phone: 49 8153282500 **E-Mail:** sausen@der.de
Fax: +49 8153281841

110 **Klaus Schafer**
Kreuzeckbahnstrasse 19
Fraunhofer-Institut fur Atmosparische Umweltforschung
D-82467 Garmisch-Partenkirchen
Germany
Phone: +49 8821 183 183 192 **E-Mail:** schaefer@ifu.fhg.de
Fax: +49 8821 73573

111 **Hans Schlager**
Instiute for Atmposheric Physics
Oberpfaffenhofen
DLR
D-82234 Wessling
Germany
Phone: +49 8153-28-2510 **E-Mail:** pa2s@vm.op.dlr.de
Fax: +49 8153-28-1841

112 **Alf Schmitt**
German Aerospace Research Establishment
Porz-Wiehnhinde, Linoler Hohe
DLR
Cologne D-51147
Germany
Phone: +49 2203 601 2182 **E-Mail:** alfons.schmitt@dlr.de
Fax: +49 2203 601 2377

113 **Ulrich Schumann**
Institute for Atmospheric Physics
Postfach 1116
DLR
D-82230 Wessling
Germany
Phone: 49 8153-28-2520 **E-Mail:** Ulrich.Schumann@dlr.de
Fax: 49- 8153-28-1841

114 **Hanwant B.Singh**
Mail Stop 245-5
Earth System Science Division
NASA/Ames Research Center
Moffett Field CA 94035-1000
Phone: 415 604-6769 **E-Mail:** hanwant_singh@gmgate.arc.nasa.gov
Fax: 415 604-3624

115 **George Slinn**
US National Academy of Sciences
2215 Benton Ave
Cascade Scientific Research Corporation
Richland WA 99352
Phone: 509 375-4150 **E-Mail:** slinnwgn@aip.org
Fax: 509 375-5116

116 **David Snape**
Moor Lane
Combustion Engineering
Rolls Royce Aerospace Division
Derby DE248BJ
United Kingdom
Phone: +44 1332 249498 **E-Mail:**
Fax: +44 1332 245654

117 **William A Sprigg**
2101 Constitution Avenue
National Research Council
Washington DC 20418
Phone: 202 334-3515 **E-Mail:** wsprigg@nas.edu
Fax: 202 334-3825

118 **Albert Stasenko**
1Zhukovsky str.
Zhukovsky Moscow Region
Central Aerohydrodynamic Institute
140160
Russia
Phone: 7095 556-4006 **E-Mail:** dfr@aerocentr.msk.su
Fax: 095 911-0019 or 556-4357

119 **Sue Stendebach**
Stratospheric Protection Division
Mail Code 6205J
Environmental Protection Agency
401 M Street, SW
Washington DC 20460
Phone: 202 233-9117 **E-Mail:** stendebach.sue@epamail.epa.gov
Fax: 202 233-9665

120 **Jennifer Stenzel**
40 West 20th Street
Natural Resources Defense Council
New York NY 10011
Phone: 212 727-4419 **E-Mail:**
Fax: 212 727-1773

121 **William Stevens**
4400 Catalina Circle
Delta air Lines, Inc.
East Point GA
Phone: 404 766-3394 **E-Mail:** bill_stevens@msn.com
Fax: 404 766-3358

122 **Richard Stewart**
Mail Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301 286-8895 **E-Mail:** stewart@oasis.gsfc.nasa.gov
Fax: 301 286-1754

123 **Richard Stolarski**
Mail Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301 286-9111 **E-Mail:** stolarski@polska.gsfc.nasa.gov
Fax: 301 286-1754

124 **Paul Stolpman**
Mailcode 6201J
Office of Atmosphere and Indoor Air Programs
Environmental Protection Agency
401 M Street, SW
Washington DC 20460
Phone: 202 233-9140 **E-Mail:**
Fax: 202 233-9586

125 **Richard Strange**
M/S 1-06
400 Main Street
Pratt & Whitney
East Hartford CT 06118
Phone: 860 564-5928 **E-Mail:** stranger@pweh.com
Fax: 860 565-3086

126 **N. Sundararaman**
Intergovernmental Panel on Climate Change
41 Avenue Guiseppe Motta
World Meteorological Organization
PO Box 2300
CH-1211 Geneva 20
Switzerland
Phone: 41 22 730 8215 **E-Mail:**
Fax: 41 22 733 1270

127 **Saadat Syed**
United Technologies
P.O. Box 109600, M/S 715-89
Pratt & Whitney
West Palm Beach FL 33410-9600
Phone: 407 796-3560 **E-Mail:**
Fax: 407 796-5825

128 **Anne M. Thompson**
Code 916
NASA/Goddard Space Flight Center
Greenbelt MD 20771
Phone: 301 286-2629 **E-Mail:** thompson@gator1.gsfc.nasa.gov
Fax: 301 286-1754

129 **Margaret A Tolbert**
Cooperateive Institute for Research in Envrionmental Science
Campus Box 216
University of Colorado, Boulder
Boulder CO 80309-0216
Phone: 303 492-3179 **E-Mail:** tolbert@colorado.edu
Fax: 303 492-1149

130 **Brian Toon**
Mail Stop 245-5
NASA/Ames Research Center
Moffett Field CA 94035-1000
Phone: 415 604-5971 **E-Mail:** toon@sky.arc.nasa.gov
Fax: 415 604-3625

131 **Adrian Tuck**
NOAA/ERL/Aeronomy Laboratory
R/E/AL6
U.S. Department of Commerce
325 Broadway
Boulder CO 80303-3328
Phone: 303 497-5485 **E-Mail:** tuck@al.noaa.gov
Fax: 303 497-5373

132 **Guido Visconti**
Dipartimento di Fisica
Gruppo di Fisica dell' Atmosfera
Universita' degli Studi L'Aquila
67010 Copito, L'Aquila
Italy
Phone: 39 862-433075 **E-Mail:** visconti@aquila.infn.it
Fax: 39 862-433033

133 **Raymond E. Walder**
Director, Engineering & Environment
2000 Peel Street
International Air Transport Association
Montreal, Quebec H3A 2R4
Canada
Phone: 514 844-6330 **E-Mail:** mm@cam.org
Fax: 514 844-6727

134 **Debra Weisenstein**
840 Memorial Drive
Atmospheric & Environmental Research Inc.
Cambridge MA 02139
Phone: 617 547-6207 **E-Mail:**
Fax: 617 661-6479

135 **Howard Wesoky**
Office of Aeronautics
Code RC
NASA Headquarters
Washington DC 20546-0001
Phone: 202 358-4650 **E-Mail:** hwesoky@aeromail.hq.nasa.gov
Fax: 202 358-3550

136 **Jan Westerberg**
Head of Corporate Environment
Vikboplan 11
Civil Aviation Administration
S-601 79 Norrkoping
Sweden
Phone: +46 11-192-249 **E-Mail:** jan.westerberg@lfv.postnet.se
Fax: +46 11-192-790

137 **Chowen Chou Wey**
Mail Stop 77-10
NASA/Lewis Research Center
21000 Brookpark Road
Cleveland OH 44135-3191
Phone: 216 433-8357 **E-Mail:** fschou@panda.lerc.nasa.gov
Fax: 216 433-3954

138 **Philip D. Whitefield**
G-11 Norwood Hall
Cloud and Aerosol Sciences Laboratory
University of Missouri, Rolla
Rolla MO 65401-0249
Phone: 314 341-4363 **E-Mail:** whitefie@umrvmb.umr.edu
Fax: 314 341-4891

139 **Upali K Wickrama**
Suite 400
1000 Sherbrooke Street West
International Civil Aviation Organization
Montreal, Quebec H3A 2R2
Canada
Phone: 514 285-8045 **E-Mail:** wickrama@icao.org
Fax: 514 285-6744

140 **Richard Wilcox**
2565 Plymouth Road
Environmental Protection Agency
Ann Arbor MI 48105
Phone: 313 668-4390 **E-Mail:** wilcox.rich@epamail.epa.gov
Fax: 313 668-4531

141 **Douglas Worsnop**
45 Manning Road
Aerodyne Research, Inc.
Billerica MA 01821-3976
Phone: 508 663-9500 **E-Mail:** worsnop@aerodyne.com
Fax: 508 663-4918

142 **Martin E. Wright**
1 Chalcot Close
Sutton Surrey SM2 6SL
Martin Wright Consulting
United Kingdom
Phone: +44 181-642-9491 **E-Mail:**
Fax: +44 181-770-9400

143 **Donald Wuebbles**
Department of Atmospheric Sciences
105 South Gregory Avenue
University of Illinois
Urbana IL 61801
Phone: 217 244-1568 **E-Mail:** wuebbles@atmos.uiuc.edu
Fax: 217 244-4393

144 **Dietmar P. Wurzel**
1627 Eye Street, NW
Suite 540
DLR German Aerospace Research Establishment
Washington DC 20006-4020
Phone: 202 785-4410 **E-Mail:** wash.office@dlrdara.org
Fax: 202 785-4410

145 **Huang Yong**
Beijing University of Aeronautics and Astronautics
China
Phone: **E-Mail:**
Fax:

146 **Yuk L. Yung**
Division of Geological and Planetary Sciences
Mail Code 170-25
California Institute of Technology
Pasadena CA 91125
Phone: 818 395-6112 **E-Mail:** yly@marcu1.gps.caltech.edu
Fax: 818 585-1917

Appendix C

DECISION MAKERS' QUESTIONS
TO THE
SCIENTIFIC, TECHNOLOGICAL, AND SOCIO-ECONOMIC COMMUNITIES
ABOUT THE
GLOBAL ATMOSPHERIC EFFECTS OF AVIATION

30 January 1996

I. INTRODUCTION

Scope. The most *familiar environmental issues* that are associated with aviation are the *explicitly local* ones of noise and air quality (e.g., smog and acidic deposition), which are primarily associated with aircraft takeoffs and landings and airport operations. For some time now, governments have been assessing and developing regulatory and other tools for local aviation environmental issues. In contrast, while global atmospheric issues have attracted considerable recent attention, a full examination of the scientific, technical, socio-economic, and policy issues associated with the global impacts of aviation's gaseous and particulate emissions has only just begun. The scope of this "discussion paper" is this *global* scene; namely, it is focused on the potential global environmental impacts of aviation that could result from atmospheric changes due to aircraft emissions. It does not include directly the more-local issues that have been examined in the past.

***Decision makers'* questions.** This brief discussion paper gives 12 major questions (with subcomponents) that decision makers in governments and in transportation-related industries currently have about the potential global environmental effects of the emissions of current and future subsonic and supersonic aircraft. These questions are posed to atmospheric scientists, to aircraft technologists, and to relevant socio-economic experts. Such questions are highly relevant to the policy process of formulating potential future international decisions regarding environmentally appropriate aircraft standards and operations in coming decades.

The *goal* of this discussion paper. The purpose of assembling this list of decision makers' questions is to enhance the effectiveness of the dialogue between decision makers and the experts who are developing the decision-relevant information related to the aviation environmental issue. This list of decision makers' questions is viewed as a first step in this enhancement.

Potential *benefits* of this list. It is realized that it is likely that not all aspects of these questions can be answered at present. However, by knowing this policy viewpoint in advance, the scientific, technical, and socio-economic communities could be better aware of the decision-making context as they produce and describe their information related to the aviation environmental issue. Specifically, this list of policy mak-

ers' questions will be provided to the attendees and speakers of the Symposium on Global Atmospheric Effects of Aviation in April, 1996, which will focus largely on the scientific and technical aspects of the aviation issue. These questions could provide a useful context for the presentations. Further, since the April Symposium is a first step in the dialogue, this list (or its subsequent updated versions) could similarly aid these expert communities in their future preparations of effective state-of-understanding assessments of the atmospheric science, technology, and socio-economics of the aviation issue.

***Format* of the list.** This discussion paper focuses first on questions that relate to the *current* understanding of the aviation issue: "What do we know now?" But, it also includes the very difficult question: "What improvements in decision-relevant information could policy makers likely expect in coming years?" Lastly, an annex is attached that summarizes, for reference, the current international decision-making organizations and the international state-of-understanding assessment entities.

II. QUESTIONS ABOUT THE STATUS OF *CURRENT* UNDERSTANDING

It is clear that the different environmental issues of today have differing degrees of current scientific and technological complexity and hence have different levels of understanding. For example, human-caused ozone-layer depletion in Antarctica has been observed and understood unequivocally for a few years now; however, the balance of evidence is only just now suggesting a discernible human influence on the global climate system. Similarly, even within a given environmental issue, some aspects are better understood than others, implying that there is not a fully homogeneous picture (i.e., emissions › perturbations › impacts). For example, it is a certainty that greenhouse gases are accumulating in the atmosphere as a result of human activities, but the resulting climatological responses are not as well documented.

The questions that are aimed at how much is known *currently* about the aviation environmental issue are in two groups. In Section A below, there are questions that ask: "Is there a problem *now*, i.e., 1996"? In Section B, there are those that ask: "What *could* it be in the future (with or without new policies)?"

A. The *Present- Day* Environmental Impacts of Aviation

Before posing focused questions about the understanding of the present global environmental effects of aviation, it is useful to ask what the main features of the issue look like.

(1) ***The broad picture.* What are the *major global environmental issues* associated with aviation?** While the supersonic-transport/ozone-layer-depletion issue is familiar from the 1970's, one hears more and more about both supersonic *and* subsonic aircraft and also about a potential role of aviation in causing "climate change". Specifically,

- o *The key features.* What is an up-to-date list of the *potential major global environmental impacts* associated with aircraft and their operations worldwide? For example: What types of emissions occur, e.g., gases such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and water vapor and particles such as soot? What are the environmental variables that could change, e.g., stratospheric ozone layer and/or the balance of infrared radiation in the atmosphere and hence climate? What types of potential human-related environmental impacts could occur, e.g., increased surface ultraviolet exposure, with related human-health impacts, and/or human-caused climate change, with related human-health, habitation, socio-economic, and other impacts?
- o *Why be concerned?* What is special about the aviation issue? What are the *key aircraft features* that gives rise to aviation being considered as a global environmental issue? For example, there is the relatively unique fact that aircraft emissions mostly occur well above the Earth's surface. What is the *basic evidence* that points to aviation as a possible issue? For example: Is it observations, predictions, and/or hypotheses?

Characterizing what is known about present-day aviation impacts poses questions that address various (admittedly interrelated) aspects of the issue: observations, predictions, and uncertainties. In short: *"How credible is this issue?"*

(2) ***Observations.* Has an aircraft-induced global environmental change actually been *observed at present?*** Examples: (i) Has a "perturbation" been seen yet; namely, has an attributed "aircraft signature" been observed in the global concentrations of trace gases or particles that are emitted by aircraft engines? (ii) Further, has a "response" been seen yet; namely, has there been any observed impact associated with aircraft emissions on the global ozone layer or on gases or particles that can effect the global climate system?

(3) ***Predictions.* For current aircraft operations, what are the global environmental changes that are *calculated* to be occurring at present, compared to a background that generally reflects the situation prior to the commercial-aircraft era?** Three aspects of the theoretical picture of the present-day aviation impacts are important to policy considerations: the magnitude, how that compares to natural changes, and how it scales against other issues that are well-known to decision makers. Namely,

- o *Calculated magnitudes and sensitivities.* As in Question (2) above, there are two "perturbation" and "response" subquestions: How much aircraft-induced trace-gas and particle perturbation are predicted to be occurring now? For example, what have been the incremental increases in CO_2 or NO_x abundances? How much corresponding NO_x-induced incremental change is occurring in the present-day ozone layer? Similarly, how much corresponding NO_x-induced radiative forcing of

climate change is predicted for today? In addition, what is the predicted sensitivity of these perturbations or the subsequent environmental responses to the major features of aircraft operations? For example, how sensitive are they to flight altitude, day-or-night flights, seasons, or geographic location?

- *Comparison to natural changes.* In addition, information that could help establish a *relative* picture would also be particularly useful. For example, compared to relevant *natural changes* of the same quantity over extended time scales (e.g., years to a decade or two), what is the predicted magnitude of the present-day aircraft-induced perturbation and responses, e.g., trace-gas concentration changes, stratospheric ozone changes, radiative-forcing changes, or climate changes?
- *Comparison to other human-influenced sources.* Similarly, what is the predicted magnitude of the present-day aircraft-induced perturbations compared to present-day perturbations of the same quantity by *other human-induced causes?* For example, how does the predicted subsonic aircraft perturbation of the radiative forcing of climate change compare to other human-caused forcings? Comparisons of *components* may be more readily available at present: How do CO_2 emissions from aircraft operations compare to those from all anthropogenic CO_2 emissions, all fossil-fuel CO_2, or CO_2 from other equivalent transportation sectors? More specifically, does current knowledge yield realistically useful aircraft-related Global Warming Potentials (GWPs) or Ozone Depletion Potentials (ODPs), similar to the policy-relevant indices used in the ozone-depletion and global-warming issues?

(4) ***Uncertainties.* How *confident* are the scientific and technical communities in the above observations and calculations in Questions (2) and (3)?** For which perturbations can quantitative uncertainty ranges be established meaningfully? For which can only the "sign" of the perturbation be established meaningfully? For which can only plausibility statements be made, e.g., "likely significant compared to natural variation"? Which are currently just hypotheses? Such answers from the expert communities are a (perhaps *the*) key input to the early steps in policy formulation, such as evoking of "precautionary principles".

B. *Future* Global Environmental Effects of Aviation

In addition to questions of the understanding of the present-day nature of the aviation issue, the atmospheric-science, aircraft-technology, and socio-economic communities are called upon to help provide a policy-relevant look to the future. Namely, the state-of-understanding assessments of atmospheric sciences, technology, and socio-economics collectively need to lay out a set of options, constructed from current knowledge, that aid policy choices. Specifically, those options need to characterize how the aviation issue *could* evolve in the future, depending upon *no* policy change and *some* policy change(s).

Questions that directly relate to the formulation of such policy-choice options largely are associated with (i) a set of future projections of the aircraft issue (based on assumed changes in a number of the aviation-relevant variables) and (ii) a set of cost-benefit analyses associated with these projections.

(5) *The aircraft-issue "variables".* **What are the major factors in establishing possible aircraft emissions over the next 30 - 50 years?** For example, the major factors that are influenceable by the aircraft industry or by governments could include engine characteristics and flight operations (e.g., altitude and geographic location). In addition, there are major factors that are *not* explicitly related to policy choices, but rather depend upon the broader context in which aviation is imbedded, and these may vary between civil and military aviation. The major external factor influencing future civil aviation is the projected growth of economic activity in the major regions of the world. Other factors include fuel prices and trends in fares. For the major factors that influence future aircraft emissions, how far into the future can these factors be truly predicted effectively, or is it more realistic just to construct a suite of possible scenarios involving them?

(6) *The interdependencies of the aircraft variables.* **What are the key interrelations between these major factors in Question (5) that introduce a correlation among choices?** For example, current engine designs have not compromised fuel efficiency in the pursuit of lower NO_x emissions. Will this continue to be the case for future designs? If not, the expected reduction in the radiative forcing of climate by lowering NO_x emissions could be nullified by the increased CO_2 emissions (and hence radiative forcing) from fuel-inefficient operations. Such information is crucial to avoiding the construction of contradictory scenarios.

(7) *Scenarios for choices.* **What is a realistic set of future aircraft-issue scenarios that can provide a useful spectrum of illustrative choices for policy considerations.** Several subquestions relate to the construction of the most realistic and useful scenarios:

- o *The appropriate environmental indicator.* Based upon current scientific, technical, and socio-economic understanding, *what is deemed the most appropriate "dependent variable" for aviation scenarios*; namely, "What" versus year? For example: Emissions versus year? Radiative-forcing/ozone-depletion versus year? Cost of impacts (i.e., several indicators in an socio-economic framework) versus year?
- o *The future, based upon current policies.* What is the best *"Business-as-usual" scenario*, based upon the current information available? This scenario is the basic and most-critical building block for a set of policy options, since it characterizes the consequences of *not* altering current aircraft environmental policies. Therefore, it is the benchmark against which other policy choices can be compared, i.e., how much improvement for a given policy change? How well can such a scenario be defined,

based upon current scientific, technical, and socio-economic understanding?

- o *The possible futures, based on a spectrum of choices.* Lastly, *what are the major "option" variables* for generating a realistic and useful set of dispersed scenarios? For example: Lower engine emissions of a specific species (e.g., NO_X) or a group of species? Changed route or operations (e.g., minimizing time in holding patterns) design?

(8) ***Costs vis-a'-vis benefits.* How can a meaningful overall *cost/benefit analysis* be done currently for the aircraft issue(s)?** This is the true end-to-end *"bottom line"* for policy. Ideally, one seeks a comparison of the full incremental *costs* of taking an action to the incremental *benefits* of all of the improved environmental impacts occurring because of the action; namely,

incremental costs incurred by the decision
◊
changed emissions
◊
changed radiative-forcing/ozone-variation
◊
changed impacts
◊
incremental costs saved by the decision.

But such an "end-to-end" analysis requires the *maximum* set of information, some of which (scientific, technical, and/or economic) may not exist or may be too crude to be useful. An information-availability survey could be a useful "reality check". Are other approaches possible? For example,

- o *Utilization of current work on other issues.* Is it possible, midway in the cost/benefit sequence above, to "piggy back" upon impact/cost evaluations that may have already been done for the broader environmental issues? For example, the socio-economic analyses of climate change impacts may have been made or may can be made for a given change in total radiative forcing. If so, the new analyses needed for the aircraft issue possibly could be only the steps: incremental costs incurred by the decision ÷ changed emissions ÷ changed radiative-forcing. The same may be true for ozone depletion and its human impacts.

(9) ***Other policy-relevant aspects.* In addition to the explicit relative cost/benefit merits among a spectrum of options, are there additional aircraft-related scientific, technical, and socio-economic factors that aid policy evaluations? Namely,**

- o *Global/local issue interrelations.* What are the linkages between the cruise-altitude policy choices and other aviation environmental issues already addressed by international aviation policies? For example, can policy choices for cruise altitude be treated as independent of other aviation

environmental issues, such as aircraft noise, airport air quality, and regional air pollution? Such understanding is important to avoid inadvertent "undoing" of past decisions.

- *Other policy aspects.* Lastly, there are other *general aspects of decisions* that pertain to the aircraft issue. Is there a "no-regrets" option(s)? Are there accompanying non-environmental benefits or detriments to the options? Even if a choice is cost effective with many benefits, are there social, political, or other types of barriers to implementing the decision? Are there practical *sets* of choices, since policies rarely rely only on one mitigation (or adaptation) measure? What is the effectiveness of different options over various decision time frames, i.e., the timing of choices? For example, does focusing on one particular option jeopardize the ability to pursue other options later? How does the costs or benefits of an aircraft decision compare to choices already made on related issues? For example, how does the annual incremental ozone depletion predicted for a future expanded fleet of supersonic aircraft compare to the magnitude of the incremental ozone-depletion reductions that were associated with recent decisions regarding halocarbons under the Montreal Protocol? (See Annex)

(10) ***The time scales involved.* Are there *atmospheric and socio-economic time scales* that are integral to the aviation issue that make early decisions different than later decisions?** For example, in the chlorofluorocarbon (CFC)/ozone-layer issue, the scientific assessments pointed out that CFCs, once released, reside in the atmosphere for decades to centuries, thereby introducing a quasi-irreversibility that implied long recovery times even after decisions were made. What are the atmospheric recovery time scales for aircraft emissions? What are the recovery times of the related environmental impacts? What are the technical lifetimes (e.g., airframe- and engine-development periods and the life expectancy) and the economic lifetimes (e.g., adequate investment return)? Which are the limiting factors, e.g., which ones would likely yield prolonged impacts as a result of a decision being made or not being made? Such information is very important for evaluating the aircraft issue with regard to a "precautionary principle".

III. QUESTIONS ABOUT THE PROSPECTS FOR IMPROVED INFORMATION IN THE FUTURE

A sequence of policy decisions on an issue often can occur over a period of time. For example, amendments and adjustments to the Montreal Protocol on ozone-layer protection have occurred every few years after the signing of the Protocol in 1987. While it is realized that unexpected discoveries and "surprises" can often abruptly change information needs and hence research directions and timetables, some general guidance about the prospects for improved information is important input to policy formulation. This general insight is, for example, part of the evaluation of the risk incurred in delaying a decision.

(11) *Likely progress in understanding.* **For the environmental changes or impacts associated with the aircraft issue, what is the likely time period for a "significant" reduction in the uncertainties noted in Question (4)?** (Assuming current levels of research.) Years? Or a decade? Or more? Even relative measures (e.g., "Aspect A will likely be understood more quickly than Aspect B.") would be useful. What are the major reasons why progress could be rapid or slow in understanding the various aspects of the aviation issue?

(12) *Comparison to progress on other issues.* **Overall, how does the complexity of the aircraft issue compare to that of other current environmental issues?** For example, how does it compare in complexity to the CFC/ozone depletion issue, which now has a 20-year history? Or to the greenhouse-gas/global-warming issue? What are the major reasons for the differences? For the similarities? These comparisons could provide some useful relative insight into possible future progress in understanding.

ANNEX: CURRENT DECISION-MAKING AND ASSESSMENT ENTITIES

The following list is a short tabulation of the current international entities that (i) are or could be making decisions about aircraft and that (ii) have carried out, in part, assessments of current understanding regarding the atmospheric phenomena related to the aircraft issue. The assessment groups have generally provided their assessed information to the decision making bodies, per the request of the latter. The assessment groups have been sponsored by international organizations, and their assessment reports have been prepared by the leading scientific, technical, and socio-economic experts worldwide.

Current United Nations Decision-Making Entities

The following international regulatory bodies are relevant to the aircraft issue. Resolutions to cooperate, as appropriate, with regard to the aircraft issue have been established in many cases.

- **International Civil Aviation Organization (ICAO).** ICAO has the leading role in international decision making regarding international aviation. Agreements exist on the environmental issues of aircraft noise and engine emissions. Regarding emissions, ICAO has established standards that new aircraft engines must meet for NO_x, carbon monoxide, and unburned hydrocarbons. While these standards were established primarily to improve local air quality and are therefore based on an aircraft's landing and take-off cycle, they probably also have helped reduce cruise emissions. The broader environmental issues associated with an aircraft's cruise cycle, such as those of the upper atmosphere, are being considered by ICAO's Committee on Aviation Environmental Protection (CAEP).

- **Convention on Long-Range Transboundary Air Pollution (1979).** The issues addressed are acid deposition and photochemical smog. Its current membership includes most European countries, Canada, and the United States of America. Three optional protocols are in force, one of which (Sofia, 1988) seeks to control emissions of NO_X. This protocol requires Parties to freeze total national emissions of NO_X at 1987 levels by 1994. While it also contains abatement measures for mobile sources, at present these are primarily aimed at motor vehicles, and aircraft are not specifically targeted.

- **Vienna Convention (1985) and its Montreal Protocol on Substances that Deplete the Ozone Layer (1987)** (and subsequent amendments and adjustments, the most recent being in late 1995). The focus has been on halocarbons (CFCs, halons, carbon tetrachloride, methyl chloroform, methyl bromide, and CFC and halon alternatives) that deplete, in varying degrees, the stratospheric ozone layer. Broader information interests include other perturbations of the ozone layer and the radiation balance, e.g., by rockets, shuttles, and aircraft.

- **Framework Convention on Climate Change (UNFCCC - 1992).** The focus has been on "classical" greenhouse gases, e.g., CO_2, methane, and nitrous oxide. Substances controlled under the Montreal Protocol are excluded. While there is agreement on an objective, namely, the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system", no specific protocol has been decided upon at present. However, countries have agreed to report their annual emissions of a listed set of greenhouse gases. Aircraft operations have been noted from the standpoint of the national accounting for fuel used in international aviation. The Convention's subsidiary bodies, such as the Subsidiary Body for Scientific and Technological Advice (SUBSTA), will be the organizational unit that would pursue other environmental aspects of aviation.

Current United Nations Scientific, Environmental Impacts, and Economic and Technology Assessment Entities

The following assessment bodies are relevant to the aviation issue. Aspects of the aviation issue have been addressed, with special or limited emphases, in some cases.

- **Scientific, Environmental Impacts, and Technology and Economics Assessment Panels of the Montreal Protocol.** The three Assessment Panels work under the auspices of the United Nations Environment Programme (UNEP) and, for the Scientific Panel, the World Meteorological Organization (WMO) and UNEP. These Panels have coordinated the relevant research communities in their production of a series of major assessments requested by the Parties to the Montreal Protocol over the past 10 years (longer for the scientific community). The focus has been on stratospheric ozone depletion, but the assessments have included broader related topics, such as radiative forcing. The past two scientific

assessments (1991 and 1994) have included a chapter focusing on the atmospheric impacts of aviation. The next scientific assessment is to be completed by the latter part of 1998, and the Panel is explicitly charged to work, as appropriate, with ICAO and IPCC (see below).

- **Intergovernmental Panel on Climate Change (IPCC).** This assessment entity works under the auspices on UNEP and WMO and has coordinated efforts of the relevant research communities over the past several years to produce two major assessments (1990 and 1995) and supplements. These have been provided to the Parties to the UNFCCC. The next full set of assessments is scheduled for the year 2000. The recent IPCC scientific assessments have commented upon aircraft emissions in their assessment of the understanding of greenhouse gases and in their assessment of the understanding of global atmospheric chemistry in general. Further, the recent IPCC assessment of mitigation options also includes some information related to aircraft emissions.

Appendix D. Overview of Major Research Programmes

This appendix was prepared following the Symposium to describe research programmes which are addressing identified scientific issues. Aviation related atmospheric research is being conducted throughout the world, and a compilation of descriptive information is maintained by the Committee on Aviation Environmental Protection of the International Civil Aviation Organization. Two particularly large programs, described here as representative of the systematic approach likely to be required to fully assess aviation's atmospheric impacts, are sponsored by the European Commission and the United States. However, all relevant research results, with emphasis on those published in peer-reviewed journals, will need to be reviewed in the international scientific assessments that are to serve as a basis for consideration of measures to control aircraft emissions.

Although organised and managed somewhat differently, the US and European programs include the following topics which are inter-related as indicated in Figure D-1 for the purpose of overall scientific assessment:

- Emissions characterisation: Characterisation of current and advanced engine emission constituents at all flight conditions.
- Near-field interactions: Study of fluid dynamics and/or chemical processes in an aircraft wake which can alter properties of engine exhaust products or their deposition altitude in any way that might significantly influence their ultimate effect on the background atmosphere.
- Operational scenarios: Development and maintenance of a three-dimensional (3-D) database representing all aircraft emissions along realistic flight paths for current and future operations.
- Atmospheric observations: Measurement of chemical and physical characteristics of the atmosphere relevant to possible effects on ozone and climate.
- Laboratory studies: Ground-based simulation and measurement of chemical and physical processes relevant to aviation.
- Global modelling: Computational models of the atmosphere to evaluate chemical and physical effects.

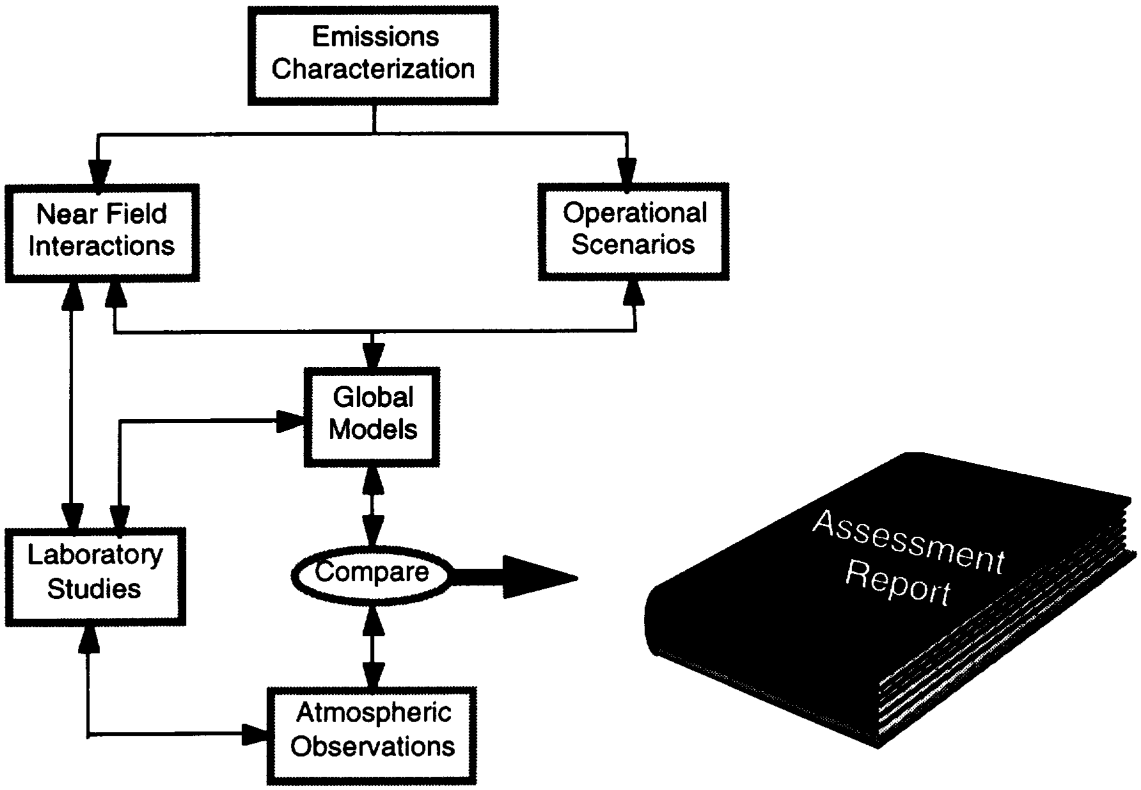

Figure D-1. Inter-relationship of Assessment Research Topics.

Together, these topical areas of research seek to answer scientific questions which can be succinctly stated as:

- What are current and future emissions from aircraft?
- What chemical and physical processes in the atmosphere could be perturbed by aircraft emissions?
- Are atmospheric observations consistent with the current understanding of aircraft emissions-related chemistry and physics?
- What are the predicted ozone changes and climatic impact associated with aviation?
- What are the uncertainties in these predictions?

A. The United States Programme

In the United States, the Atmospheric Effects of Aviation Project (AEAP) is managed and conducted by the National Aeronautics and Space Administration, in

co-operation with the Federal Aviation Administration and in collaboration with other research Agencies, such as the National Oceanic and Atmospheric Administration (NOAA). A Steering Committee, with members from participating industry, scientific and regulatory organisations, insures cognisance of AEAP by those engaged in related activities, promotes research co-ordination, provides guidance on partitioning of project funds, and recommends new research tasks. The National Research Council's Panel on Atmospheric Effects of Aviation evaluates the project research plan, accuracy of results relative to current state of scientific knowledge, and identification of key uncertainties. In addition, the Panel suggests other research likely to reduce uncertainties prior to and after the end of the planned effort in 2001.

AEAP began as an element of the NASA High-Speed Research Program (HSRP) in 1990. The HSRP is conducting research and developing technology for a second-generation supersonic transport (AKA high-speed civil transport (HSCT)) that could be operable early in the next century. The Atmospheric Effects of Stratospheric Aircraft (AESA) element is evaluating the possible effects of a large fleet of HSCT aircraft on stratospheric ozone which, as described elsewhere in this report, affects both ultra violet radiation and climate.

In 1994, the Subsonic Assessment (SASS) was added to AEAP as an element of the NASA Advanced Subsonic Technology Program (ASTP), a broad ranging research and technology effort involving many topics. Understanding how oxides of nitrogen (NO_x) in aircraft engine exhaust control ozone is also a SASS objective, but equal emphasis is given to other emittants which affect climate either through atmospheric chemistry or radiative processes; again as described elsewhere in this report. Interim assessment reports for the AESA element of the US endeavour have been published by NASA and the research results incorporated in international scientific assessments. The first US subsonic assessment report is planned for publication in early-1997.

Because knowledge of the relevant atmospheric chemical and physical processes is lacking, the major portion of AEAP resources is devoted to atmospheric observations, particularly in situ measurements. Several aircraft are being utilised as instrument platforms in a large number of field campaigns, each with a specific goal but related to the overall project in a systematic manner. Between 1995 and 1997, a NASA ER-2 aircraft is extending a database of process studies in the Stratospheric Tracers of Atmospheric Transport (STRAT) campaign. These measurements of seasonal and latitudinal variations in ozone related atmospheric dynamics are complemented at altitudes above 20 km by balloon based instruments in the Observations from the Middle Stratosphere (OMS) project. In the summer of 1997, it is planned to complete the AESA sponsored observations with the Photochemistry of Ozone Loss in the Arctic Region in Summer (POLARIS) which will finish a series of ER-2 based measurements investigating the photochemical controlling mechanisms for ozone in the lower stratosphere. In particular, these latter studies will compare the relative roles of oxides of nitrogen (i.e., which are the primary concern) with halogen and hydrogen species.

Atmospheric observations that more directly support SASS began in the Spring of 1996 with the Subsonic Aircraft Contrail and Cloud Effects Special Study (SUCCESS) which had several objectives:

- Determine the radiative properties of cirrus clouds and contrails so that satellite observations can more reliably measure their impact on Earth's radiation budget.

- Determine how cirrus clouds form, whether the exhaust from subsonic aircraft presently affects the formation of cirrus and, if the exhaust does affect the clouds, whether the induced changes are of climatological significance.

- Develop and test several new instruments.

- Characterise gaseous and particulate exhaust products from subsonic aircraft and their evolution in the region near the aircraft.

The NASA DC-8, and T-39 aircraft were used as in situ sampling platforms, and the ER-2 aircraft as a remote sensing platform. The NASA B-757 was used as a source aircraft for studies of contrails and engine exhaust. Results from SUCCESS will be published during the coming year.

In the Summer of 1997, the SASS Ozone and NO_x Experiment (SONEX) will primarily utilise the NASA DC-8 Flying Laboratory to study the atmospheric chemistry of ozone and its precursors in and around the North Atlantic flight corridors. Later field campaigns are planned to study the importance of lightning to the production of NO_x and the dynamics of convection during storms which carry emissions from near ground level to the upper troposphere and lower stratosphere. All of these atmospheric observations utilise many instruments which have been developed primarily within government sponsored research programs, and are capable of measuring very small traces (e.g., parts per billion by volume) of relevant chemical species at high frequency (e.g., one hertz). And significant collaboration occurs for each field campaign with other US, European or international programs.

In the current US program, development of computer simulations of the atmosphere is concentrated in the Global Modelling Initiative (GMI), a 3-D community model which will be utilised in future assessments. GMI will allow the best contributions of a number of organisations to be applied in a well documented, systematic manner beginning with the 1998 report on stratospheric studies. It will later serve as a principal tool for subsonic assessments. Inputs for the modelling studies and the overarching assessments are provided by other AEAP elements corresponding to the topics of Figure D-1.

Laboratory studies are generally reported on a biannual basis by the NASA Panel for Data Evaluation. Emissions characterisation is being accomplished in lab-

oratory level combustion research facilities, in rigs simulating sectors of aircraft engine combustors, and with actual engines. Generally because of commercial proprietary considerations, US engine level measurements are utilising military test articles. However, inflight measurements of "near field interactions" are utilising actual civil aircraft (e.g., the NASA B-757 noted above). And these measurements are being used to test the validity of computational models for the fluid mechanical and chemical processes. Emission inventories are being developed by Boeing and McDonnell Douglas which simulate current fleet operations (i.e., number and type of aircraft, flight paths, level of emissions) or forecast future scenarios.

B. The European Commission Programme

The European efforts concerning the atmospheric impacts of aircraft emissions are conducted by the Environment and Climate Research Programme of the European Commission (EC) as well as by national programmes of the Member States of the European Union. Research activities complementary to the aircraft impacts on engine technologies for reducing the aircraft emissions are supported by the EC Industrial and Material Technologies (IMT) Research Programme (Area 3: Aeronautics). Both programmes are part of the multiannual Framework Programmes of the DG XII/EC for RTD activities in Europe. The European activities in this field, which are described here, can be divided for practical reasons in two periods. The first includes activities supported under the 3rd Framework Programme for R&D activities which covered the period from 1992 up to 1996, while the second period started in early 1996 and is supported under the 4th Framework Programme. These current activities will be supplemented by additional efforts as result of the new call for proposals of the Environment and Climate Programme launched by the EC in September 1996, with possible start of the projects in mid-1997.

Taking into consideration the US programme on supersonic transport effects, the European efforts have been concentrated since 1992 on the effects of subsonic transport with increasing support. For the first time, an integrated study aiming to a better understanding of the atmospheric effects of emission of subsonic aircraft, the AERONOX project 1992-1994, was supported under the Environment Research Programme. After the initiation of AERONOX, further research activities have been supported by the European Commission dealing mainly with field measurements such as the POLINAT, MOZAIC, STREAM and AEROTRACE projects. At a national level, a considerable number of individual programmes on aircraft impacts have also been initiated, such as the "Comité Avion Ozone" in France, the "Pollutants from Air Traffic, Effects and Prevention" in Germany, the "Air Traffic and Pollution (Lulu)" in the Netherlands, the "Flight levels" in the United Kingdom, etc. In parallel, trans-national co-operation of aircraft programmes, mainly on technological aspects, has been started by the creation of the Association of European Research Establishments in Aeronautics (AEREA).

The AERONOX project has dealt mainly with NO_x engine exhaust emissions, physics and chemistry in the aircraft wake and global atmospheric modelling simulations. AERONOX resulted in improved estimates to determine NO_x emissions at cruise conditions based on available data for aircraft/engine combinations and NO_x emission measurements on two engines (Rolls-Royce RB211 and Pratt-Whitney PW305) in simulated cruise conditions. This information was combined with a traffic database by the ANCAT-group (Abatement of Nuisances Caused by Air Traffic) of the European Civil Aviation Conference (ECAC), which was supported by DG XI (Environmental Policy) of the EC to provide detailed information on global air traffic pathways and to enable the establishment of the ANCAT/EC NO_x emission inventory.

The POLINAT project (Pollution from aircraft emissions in the North Atlantic flight corridor) project carried out two measurement campaigns west of Ireland in November 1994 and July 1995 using a Dassault Falcon aircraft. POLINAT studied the composition, the spatial and temporal distribution and the transformation of pollutants emitted from jet engines of subsonic air traffic at cruise altitudes near the tropopause within the eastern part of the North Atlantic flight corridor. Emissions from air traffic in terms of NO_x, HNO_3, SO_2, H_2O and particles were measured. The STREAM project (Stratosphere Troposphere Exchange Study by Aircraft Measurements) performed two campaigns using a Cessna Citation aircraft able to fly up to 13 km : one in July 1994 in a westerly direction from Amsterdam to study vertical exchange processes in cold fronts from the North Atlantic Ocean and the other in February 1995 in the Northern Sweden to study local denitrification of the lower stratosphere through heterogeneous processes. The MOZAIC (Measurements of OZone by Airbus In-service airCraft) project is performing large scale continuous in-situ measurements of ozone and water vapour aboard 5 Airbus A340 in-service aircraft of four airlines. Its objective is to constitute a databank on atmospheric composition at altitudes 0-13 km and to study the impact of subsonic aircraft on the atmosphere by improving basic knowledge of atmospheric chemistry. The AEROTRACE project (measurements of trace species in the exhaust from aero-engines), still operational, provides quantitative data on the emissions of trace species (particulates, nitrogen species, speciated hydrocarbons) from aircraft engines over the entire flight cycle, using available and established on-line and off-line analytical techniques in combination with gas sampling.

Within the 4th Framework Programme, the EC reinforced its activities in the field of aircraft impacts on the atmosphere and the tropospheric-stratospheric exchange studies. Seven projects in the Environment and Climate Programme (POLINAT II, STREAM II, CARIBIC, AEROCHEM, MOZAIC II, AEROCONTRAIL and TOASTE-C) and one in the IMT Programme (AEROJET) started in early 1996 (Table 1). These eight projects compose a cluster which complement research activities at the European level on stratospheric ozone depletion and on tropospheric chemistry. Coordination of these activities is implemented through the EC Advisory Science Panels on stratospheric ozone and on atmospheric chemistry (tropospheric issues) and the European Ozone Research Coordinating

Unit located in Cambridge, UK. The coordination strategy which was developed during the last years ensures that projects directly concerned with aircraft impact studies are strongly linked with many other projects devoted to a better understanding of the basic properties of the atmosphere, in order to maximise the mutual scientific benefit.

This cluster of eight projects is contributing also to the objectives of the EC Aeronautic Task Force "Next Generation Aircraft" which aims to implement a strategic and integrated approach in the whole aeronautics chain. The objectives of the Task Force include the application of advanced technologies, reduction of cost and time scales, demonstration and validation of technologies which improve the overall efficiency of aircraft, reduce noise and emissions of aircraft and, finally, minimise the impacts of aircraft emissions in the atmosphere.

Finally, in order to review the present state of knowledge (based not only on the EC funded research) the EC initiated a European Assessment on the atmospheric impact of both subsonic and supersonic aircraft on the upper troposphere and the lower stratosphere, scheduled to be finished early 1997. The assessment includes the open questions relevant to the aircraft problem, the key physical and chemical processes occurring in the atmosphere, estimates of air traffic and aircraft emissions, the effects on the chemical composition of the atmosphere at local, regional and global scale and finally the effects on climate forcing. The goal is to provide the best scientific information available for making appropriate decisions regarding the future development of aircraft operations.

Table 1 - List of EC Projects 1996-1997
POLINAT II (Pollution from aircraft emissions in the North Atlantic flight corridor) In situ measurements in the eastern part of the North Atlantic flight corridor using a Dassault Falcon aircraft which will be combined with simultaneous measurements on board a Swissair Boeing 747 flying within the corridor. These POLINAT/EC measurements will be coordinated in Summer 1997 with those of SONEX/NASA which will be carried out in the western part of the corridor.
STREAM II (Stratosphere troposphere exchange studies by aircraft measurements) It involves instrument improvements, two measurement campaigns and associated modelling studies. The aircraft measurements will be coordinated with balloon soundings to study a) pollutant transports in extratropical cyclones that advance over Europe from the Atlantic Ocean and b) southward transport of O_3 depleted air in the lower stratosphere after break-up of the Arctic vortex.
CARIBIC (Civil aircraft for remote sensing and in-situ measurements in troposphere and lower stratosphere based on the instrumentation container concept) Development and deployment of an automatic multiphase measuring system, which will fly regularly on a in-service aircraft of LTU over various parts of the globe. The measurements include a suite of trace gases together with aerosol size distribution and chemical composition : CO, O_3, CxHy, COS, SF_6, particles, etc.
AEROCHEM (Modelling of the impact on ozone and other chemical compounds in the atmosphere from airplane emissions) It is to study how past, present and future aircraft emissions affect ozone in the upper troposphere and lower stratosphere. The main tools will be global 3-D chemical tracer models where large scale ozone distribution and changes due to aircraft are calculated. These models will be supplemented by regional 2-D model studies. Results from these model calculations will contribute to the European Assessment.
MOZAIC II (Measurements of ozone by Airbus in-service aircraft) It is a continuation of MOZAIC I (5 in-service aircraft, 0_3 and H_2O). Feasibility study of new airborne devices (NOy chemiluminescence and CO resonance fluorescence) is also foreseen. The project includes interpretation of both MOZAIC I and II data and model validation studies to gain better understanding of atmospheric chemistry and dynamics.
AEROCONTRAIL (Formation processes and radiative properties of particles in aircraft wakes) It intends to provide further knowledge on the interaction between aircraft emissions, cloud and particle formation (contrails) and radiative energy transfer in the upper troposphere. The project combines aircraft "in situ" observations (Dassault Falcon) in the wake, ground based observations by lidar and numerical modelling.
TOASTE-C (Transport of ozone and stratosphere troposphere exchange) It will investigate the physical and chemical processes involved in stratosphere troposphere exchange in extra-tropics by series of field measurements and model case studies. Measurements will be carried out by an airborne ozone lidar (in a F27 aircraft), ground-based ozone and temperature lidars, radars and ozone sondes while the modelling capability includes GCM, mesoscale, mechanistic and chemical models.
AEROJET (Non-intrusive measurements of aircraft engine exhaust emissions) Fourier Transform Infrared and Narrow-Band Spectroscopy will be used as non-intrusive measurement techniques for analysis of aircraft engine exhaust emissions in industrial test rigs. The objective is to identify the most appropriate and versatile non-intrusive techniques and instrumentation to replace the current conventional methods for industrial operational use.

Appendix E. Glossary of Selected Terms

Aerosols – Airborne particles. The term has also come to be associated, misleadingly, with the propellant used in "aerosol sprays".

Albedo – Reflectivity of clouds, land, ocean, ice, or snow surfaces to incident solar radiation.

Antarctic ozone hole – A substantial reduction below the naturally occurring concentration of ozone over Antarctica.

Antarctic polar vortex – An enormous ring of moving air created by powerful stratospheric winds that blow in a clockwise direction around the Antarctic continent during the winter months.

Catalytic cycle – Refers, in these proceedings, to a cycle of chemical reactions, involving several chemical compounds, that results in the destruction of ozone molecules by ionised chlorine atoms.

Climate change – Climate change, as referred to in the observational record of climate, occurs because of internal changes within the climate system or in the interaction between its components, or because of changes in external forcing either for natural reasons or because of human activities. It is generally not possible clearly to make attribution between these causes. Projections of future climate change reported by IPCC generally consider only the influence on climate of anthropogenic increases in greenhouse gases and other human-related factors.

Climate model – A numerical simulation of the climate system. Climate models are of two basic types: (1) static, in which atmospheric motions are neglected or are represented with a simple parameterization scheme such as diffusion, and (2) dynamic, in which atmospheric motions are explicitly represented with equations. The latter category includes general circulation models (GCMs).

Contrail - Condensation trails, i.e., the line cloud often visible behind aircraft.

Dp/Foo - the ICAO regulatory parameter for gaseous emissions, expressed as the mass of the pollutant emitted during the Landing / Take-Off (LTO) cycle divided by the rated thrust (maximum take- off power) of the engine.

Emission index (EI) - The mass of emitted materials per burnt mass of fuel (for NO_x in g of equivalent NO_2 per kg of fuel, for hydrocarbons in g of CH_4 per kg of fuel).

Engine pressure ratio - The ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the

compressor entry plane, when the engine is developing its take-off thrust rating (in ISA sea-level static conditions).

Feedback – In climate studies, the amplification (positive feedback) or dampening (negative feedback) of climate change by climatic processes that are a consequence of the change.

Greenhouse gas – A gas that absorbs radiation at specific wavelengths within the spectrum of radiation (infrared radiation) emitted by the Earth's surface and by clouds. The gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planetary surface. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.

Heterogeneous chemistry – A category of chemical reactions that involve both gaseous and liquid/solid ingredients.

Landing / Take-off (LTO) cycle - A reference cycle for the calculation and reporting of emissions, comprising 4 power settings and related operating times for subsonic aircraft engines (Take-off - 100% power, 0.7 minutes; Climb - 85%, 2.2 min.; Approach - 30%, 4.0 min.; Taxi/Ground Idle - 7%, 26.0 min.).

NOx - Oxides of nitrogen, defined as the sum of the amounts of nitric oxide (NO) and nitrogen dioxide (NO2) calculated as if the NO were in the form of NO2.

Ozone (O_3) – A gas that is formed naturally in the stratosphere by the action of ultraviolet radiation on oxygen molecules. A molecule of ozone is made of up three atoms of oxygen.

Ozone layer – A layer of ozone gas in the stratosphere that shields the earth from most of the harmful ultraviolet radiation coming from the sun.

Polar stratospheric clouds (PSCs) – Large, diffuse, ice-particle clouds that form in the stratosphere usually over polar regions.

Polar vortex – In the stratosphere, a strong belt of winds that encircles the South Pole at mean latitudes of approximately 60°S to 70°S. A weaker and considerably more variable belt of stratospheric winds also encircles the North Pole at high latitudes during the colder months of the year.

Radiative forcing – A simple measure of the importance of a potential climate change mechanism. Radiative forcing is the perturbation to the energy balance of the Earth-atmosphere system (in W m^{-2}) following, for example, a change in the concentration of carbon dioxide or a change in the output of the Sun; the

climate system responds to the radiative forcing so as to re-establish the energy balance. A positive radiative forcing tends to warm the surface and a negative radiative forcing tends to cool the surface. The radiative forcing is normally quoted as a global and annual mean value. Sometimes called "climate forcing".

Rated output - The maximum thrust available for take-off under normal operating conditions, as approved by the certificating authority.

Reservoir molecules – Molecules in the atmosphere that bind with atoms or other molecules and prevent them from participating in chemical reactions.

Specific fuel consumption (SFC) - The fuel flow (generally in weight/hour) per unit of thrust developed by an engine.

Stratosphere – The highly stratified and stable region of the atmosphere above the troposphere (see below) extending from about 10 km to about 50 km.

Troposphere – The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and "weather" phenomena occur. The troposphere is defined as the region where temperatures generally decrease with height.

Ultraviolet (UV) radiation – Energy waves with wavelengths ranging from about 0.005 to 0.4 micrometers on the electromagnetic spectrum. Most ultraviolet rays coming from the sun have wavelengths between 0.2 and 0.4 micrometers. Much of this high-energy radiation is absorbed by the ozone layer in the stratosphere.

Drawn from (i) *Climate Change 1995, The Science of Climate Change, Summary for Policymakers,* Intergovernmental Panel on Climate Change (1996); (ii) *Ozone Depletion, Greenhouse Gases, and Climate Change,* U.S. National Research Council (1989); and (iii) *Investigating the Ozone Hole,* R. L. Johnson, Lerner Publications, Minneapolis (1993).

Appendix F. Bibliography

Amanatidis, G.T. and Ott, H., European Commission research on stratospheric ozone depletion, Phys. Chem. Earth, Vol. 20, N°1, pp 13-19, 1995.

Amanatidis, G.T. and Harris, N., European stratospheric ozone research 1996-97, Air Pollution Research Report, EC, Brussels, Report No. 59, EC, Brussels, EUR 16987, 1997.

Angeletti, G. and Amanatidis, G.T., European Commission Research on tropospheric physics and chemistry 1995-98, Proceeding of the EUROTRAC Symposium '96, Computational Mechanics, vol. 2, p. 21-25, 1996.

Brasseur, G., Cox, R.A., Isaksen, I., Lelieveld, J., Lister, D., Schumann, U. and Wahner, A., Assessment on atmospheric impact of both subsonic and supersonic aircraft on upper troposphere and lower stratosphere, EC, Brussels, in preparation, 1997.

Friedl, R.R. et al., 1996 Interim Assessment of the Atmospheric Effects of Subsonic Aircraft, NASA Reference Publication, 1997.

Houghton, J.T. et al. , editors, Climate Change 1995: The Science of Climate Change, Intergovernmental Panel on Climate Change, Cambridge University Press, 1996.

Howard, R.P., editor, Experimental characterisation of gas turbine emissions at simulated flight altitude conditions, United States Air Force, AEDC-TR-96-3, 1996.

International Civil Aviation Organization, Investment requirements for aircraft fleets and for airport and route facility infrastructure to the year 2010, ICAO Circular 236-AT/95, 1992.

International Civil Aviation Organization, International Standards and Recommended Practices, Annex 16 - Environmental Protection, Volume II - Aircraft Engine Emissions, Second Edition, July 1993.

International Civil Aviation Organization, ICAO Engine Exhaust Emissions Data Bank, First Edition - 1995, ICAO Doc 9646-AN/943.

International Civil Aviation Organization, Report of the Committee on Aviation Environmental Protection, Third Meeting, 5-15 December 1995, ICAO Doc 9675, CAEP/3.

Schumann, U., AERONOX, The Impact of NO_x Emissions from Aircraft Upon the Atmosphere at Flight Altitudes 8-15 km, EC, Brussels, EUR 16209, 1995.

Schumann, U., POLINAT, Pollution from aircraft emissions in the North Atlantic flight corridor, Air Pollution Research Report, EC, Brussels, Report No. 58, EC, Brussels, EUR 16978, 1996.

Stolarski, R.S. et al., 1995 Scientific Assessment of the Atmospheric Effects of Stratospheric Aircraft, NASA Reference Publication 1381, November 1995.

Thompson, A.M., R.R. Friedl and H.L. Wesoky, editors, Atmospheric Effects of Aviation: First Report of the Subsonic Assessment Project, NASA Reference Publication 1385, May 1996.

World Meteorological Organization, Scientific Assessment of Ozone Depletion: 1994, Global ozone Research and Monitoring Project - Report No. 37, February 1995.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (leave blank)	2. REPORT DATE May 1997	3. REPORT TYPE AND DATES COVERED Conference Proceedings
4. TITLE AND SUBTITLE Global Atmospheric Effects of Aviation: Report of the Proceedings of the Symposium		5. FUNDING NUMBERS
6. AUTHOR(S) D.L.Albritton, G.T.Amanatidis, G.Angeletti, J.Crayston, D.H.Lister,M.McFarland, J.M.Miller, A.R.Ravishankara, N.Sabogal, N.Sundararaman, H.L.Wesoky		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Office of Aeronautics and Space Transportation Technology		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA-CP-3351
11. SUPPLEMENTARY NOTES		
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category - 45		12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

The objective of the Symposium on the Global Atmospheric Effects of Aviation was to bring international scientific, technology, and policy leaders together to review the status of all relevant atmospheric research, for discussion of potential mitigation measures, and to consider what policy-relevant information may be available to decision makers in the next few years. Capsules of discussions of various facets of the issue comprise the main body of the report. Included in a summary of discussions regarding the way forward was recognition for the value of a single international scientific/technical assessment regarding the current understanding of the impacts of aircraft emissions on the global atmosphere.

14. SUBJECT TERMS aviation, aircraft, emissions, environment, climate, ozone			15. NUMBER OF PAGES 96
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclass	18. SECURITY CLASSIFICATION OF THIS PAGE Unclass	19.SECURITY CLASSIFICATION OF ABSTRACT Unclass	20. LIMITATION OF ABSTRACT Unlimited

Available from NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390